The outcomes of directionality: Towards a morphology of sociotechnical systems

Environmental Innovation and Societal Transitions 40 (2021) 108–131

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

The outcomes of directionality: Towards a morphology of sociotechnical systems

John Andersson, Hans Hellsmark, Björn Sandén #

Division of Environmental Systems Analysis, Department of Technology Management and Economics, Chalmers University of Technology in Gothenburg, Sweden

ARTICLE INFO

Keywords:
Morphology
Directionality
Sociotechnical system
Technological innovation
Sustainability transitions

ABSTRACT

The sustainability transitions literature departs from the idea that grand challenges such as climate change and rising inequality call for far-reaching changes in sociotechnical systems of production and consumption. This implies a dual interest in the directionality of innovation; some directions of change can be perceived as more desirable, while others may be more plausible due to the path dependent nature of sociotechnical change. The specific characteristics of the potential outcomes of directionality have, however, received little attention. Our aim is therefore to unpack and conceptualize the multidimensional space in which sociotechnical systems may adopt different shapes and configurations. We also provide three illustrative empirical examples where directionality has resulted in systems with different technical, social and spatial characteristics. The ideas put forward in this paper can be seen as a contribution to a morphology of sociotechnical systems and thereby support efforts to investigate or promote specific directions of change.

1. Introduction

The sustainability transitions literature departs from the idea that grand challenges, such as climate change (IPCC, 2018, 2014), biodiversity loss (IPBES, 2019) and rising inequality (UN, 2020), call for fundamentally different patterns of production and consumption in society (Köhler et al., 2019). Transitions scholars conceptualize the far-reaching changes required to shift these patterns as the emergence, reconfiguration and decline of sociotechnical systems, while emphasizing that innovation is path dependent and systemic (Bergek et al., 2015, 2008b, 2008a; Geels, 2005, 2002; Markard et al., 2012; Markard and Truffer, 2008; Rip and Kemp, 1998). This implies a dual interest in the directionality of innovation; some directions of change can be perceived as more desirable from a sustainability perspective, while others may be more plausible due to path dependence. Nevertheless, criticism has been raised that transitions research is not sensitive enough to the diversity of potential directions within any broadly framed transition (Stirling, 2011). Directionality is generally construed broadly by focusing on sociotechnical systems that are considered in line with social and environmental objectives. Conceptual and empirical contributions describe and explain the dynamics which underlie the growth of such systems, but pay less attention to the specific characteristics of their shapes and configurations (Andersson, 2020).

While building knowledge about how the growth of desirable sociotechnical systems can be promoted by policymakers and other actors is certainly worthwhile, this alone may result in ignorance with regards to undesirable development trajectories. For example,

Abbreviations: (R&D), Research and development; (PV), Solar photovoltaics.

Corresponding author.
E-mail address: bjorn.sanden@chalmers.se (B. Sandén).

https://doi.org/10.1016/j.eist.2021.06.008
Received 31 August 2020; Received in revised form 14 April 2021; Accepted 21 June 2021
Available online 5 July 2021

any sociotechnical system involves alternative production methods, and some of these may be preferable due to lower impact on health, the environment or resource depletion. To ensure resilient and competitive markets, there are also reasons to favor industrial configurations in which production is distributed among several firms and regions, rather than concentrated to a monopolistic actor in a specific place.[1] Moreover, when adopting a national or regional perspective, the problems associated with some trajectories become even more apparent, since the realization of many common policy objectives, such as job creation and increased tax revenue (EU, 2009; IRENA, 2014; Joas et al., 2016), depends on where new industries emerge. It should also be noted that some trajectories are certainly preferable from a growth perspective as well, since they may promote configurations that, for example, facilitate collaborative learning among developers, producers and users of new products (Cooke, 2002; Cooke et al., 1997; Porter, 1990; Saxenian, 1990).

Although transitions scholars increasingly emphasize that also sociotechnical systems perceived as desirable can develop along different trajectories (Pel et al., 2020; Stirling, 2011, 2009, 2008; Weber and Rohracher, 2012; Yap and Truffer, 2018), the literature does not offer a comprehensive conceptualization of the multidimensional space in which these trajectories appear. Instead, there is a strong focus on the dynamics which underlie the formation of directionality, while its outcomes are rarely defined beyond alternative technologies. This makes us take a step back from dynamics, causal explanations, governance and participatory processes, and instead search for distinguishing characteristics of the directions themselves. Inspired by the early work of Zwicky on the morphological approach (Ayres, 1969; Foray and Grübler, 1990; Jantsch, 1967; Ritchey and Arciszewski, 2018; Zwicky, 1967), we thus seek to contribute to the development of a *morphology of sociotechnical systems*.

Our more specific aim is to unpack and conceptualize the multidimensional space in which sociotechnical systems may adopt different shapes and configurations. To illustrate our conceptual contribution, we also provide three illustrative empirical examples where directionality has resulted in systems with different technical, social and spatial characteristics.[2] Combined with insights into innovation dynamics and directionality presented in the extant sustainability transitions literature, and the understanding of social and environmental consequences developed in the technology assessment community,[3] the ideas presented in this paper may support both analysts and policymakers with an interest in investigating and promoting specific directions of change.

After this brief introduction, Section 2 discusses how the direction of sociotechnical change has been framed historically, reviews how directionality is conceptualized and investigated in contemporary transitions research, and elaborates on the need to develop a morphology of sociotechnical systems. Section 3 then presents our conceptual contribution, while Section 4 provides three illustrative empirical examples. Finally, we summarize our ideas in Section 5 and suggest some avenues for further research.

2. The direction of sociotechnical change

2.1. Contrasting historical perspectives on technological innovation and directionality

Thinkers of the last two centuries have linked technological innovation and societal development in different ways. One admittedly coarse, but nevertheless useful, dichotomy is between perspectives that relate innovation to one-dimensional progress and those that highlight the multiplicity of possible directions. The former perspective is manifested in an influential stream of thought taking root in the scientific and early industrial revolution. Expressed by writers such as Condorcet and Comte, technological innovation is here conceived and conceptualized as a force leading to societal progress (Liedman, 1997). In the 20th century, the ideas of enlightenment and progress were relabeled and narrowed down to 'economic growth', taking the form of an almost uncontested one-dimensional societal goal, underpinned by the emerging field of economics (Stirling, 2009).

The other perspective instead stresses that society may choose between different paths in a multidimensional space of technological possibilities and that the choice of direction strongly influences the development of society. While there have always existed writers and thinkers with a pessimistic view of how technology influences society, the post-war period saw a new type of critique coming from within the field of science and technology. The growing awareness of the risks associated with increasingly potent technology and unconstrained economic growth led scientists such as Zwicky and Gabor to plea for a governance of technology and a careful consideration of the direction of sociotechnical change (Gabor, 1963; Zwicky, 1967). Aspirations for a new type of scientifically based and goal-oriented management of technology and social change emerged, inspired by cybernetics (Wiener, 1948), operations research (Page, 1967) and general systems theory (Bertalanffy, 1968). The future was not closed but open, and there were tools that could be used to investigate and normatively assess alternative directions (de Jouvenel, 1967; Jantsch, 1967). Societal development became a matter of planning and design, something that could be studied and shaped, to reap the fruits of innovation while avoiding detrimental consequences (de Jouvenel, 2019). The central position of technology choice was manifested in the creation of formal organizations such as the "Office of Technology Assessment" in the US (Coates, 1972), in the emergence of many state funded futures studies (de Jouvenel, 2019), and in the society wide debates on the Limits to Growth (Meadows et al., 1972).

[1] The need to balance the benefits of economies of scale against the increased resilience brought by distributed industrial configurations was utterly apparent during the global Covid-19 pandemic, which was raging at the time of writing this paper.

[2] The examples are based on empirical material from case studies partly reported in other publications by members of the author group (see e.g. Andersson et al. (2021), Hojcková et al. (2018) and Hellsmark and Hansen (2020)).

[3] By the term "technology assessment" we refer to a broad field concerned with assessing technologies in terms of their environmental, health, social and political impacts covering many sub-fields, such as life cycle assessment and risk assessment, rather than the more narrow strand that currently use the label "technology assessment".

However, while the urgent nature of the problems facing industrial society did not fade, the optimism surrounding societal planning did. From one corner, the quantitatively oriented systems science was criticized for being naïve and not acknowledging that social problems are "wicked" (Andersson et al., 2018; Churchman, 1967; Rittel and Webber, 1973). There is not one optimal solution to anything at the societal level where different stakeholders have different norms, interests and power. Social and technological change is accordingly a process of negotiation, not calculation and optimization. From more or less the opposite corner, neoliberal thinkers gained ground postulating that the government should stay away from picking winners and losers and leave technology selection to market forces. Later this led to the mantra that government policy should be "technology neutral" (Azar and Sandén, 2011), which in effect means that the direction of technological progress in not an issue for political debate and deliberation. Technological innovation was once again reduced to a one-dimensional force, developing somehow exogenously, enabling the economy to grow by pushing a 'production possibility frontier'. The critique did not only reduce the belief in planning at the societal level, but also in essence rejected the notion of *normative directionality* – that some directions can be better than others. From neoliberal as well as postmodern perspectives, the future is best handled by myopic market transactions, or negotiation, at the micro level. Accordingly, the US Office of Technology Assessment was dismantled in 1995, and futures studies was a thing of the past.

In parallel, in a smaller scientific niche, evolutionary economists were rediscovering what we may term *positive directionality* – that some directions are more plausible than others since their formation depends on historical decisions. Combining ideas from evolutionary biology and systems thinking with examples from history of technology, Arthur (1988) and David (1985) demonstrated that technological innovation is path-dependent; one configuration may be selected out of chance but then reinforced by positive feedback (increasing returns to adoption). Once a certain configuration is established it is stabilized through processes of homeostasis (Saviotti, 1986); it forms a 'dominant design' (Abernathy and Utterback, 1978), 'technological regime' (Nelson and Winter, 1982) or 'technological guidepost' (Sahal, 1981); and development hence follows a 'natural trajectory' (Nelson and Winter, 1982) or 'technological paradigm' (Dosi, 1982), while other options are excluded. In history and sociology of technology, Pinch and Bijker (1987) and Hughes (1987), respectively, used the terms closure and momentum to describe similar phenomena of selection and inertia, and also broadened the discussion to include additional sets of sociotechnical elements. As in biological evolution (Eldredge and Gould, 1972) and science (Kuhn, 1970), change in a certain technological field is thus characterized by periods with a relative openness to change in different directions, while this window of opportunity is later closed, locking change into narrower paths (Sartorius and Zundel 2005).

With the global discourse around sustainable development in the 1980s and 1990s (WCED, 1987) the normative directionality returned. When combined with positive directionality it was evident that path dependence hindered a swift shift to, for example, low carbon technologies, since the old carbon based energy 'regime' blocked novelties from breaking through (Foray and Grübler, 1996; Kemp, 1994; Kemp and Soete, 1992; Unruh, 2000). In addition, path dependence implied that a myopic view on the choice of future technologies is risky, since 'the market' may pick and lock in winners that are appealing in the short term but have low potential or detrimental longer term consequences (Andersson and Jacobsson, 2000; Sandén, 2004).

This combined attention to what we here have termed normative and positive directionality of technological innovation led to the broad school of thought now commonly referred to as sustainability transitions research (Köhler et al., 2019; Van Den Bergh et al., 2011). As opposed to innovation or transformation, a transition is a transition to something. It is a concept that connects the present to an endpoint and thereby implies a direction, which in this field is normatively based – something more 'sustainable'. At the same time transitions scholars typically acknowledge that sociotechnical change is path dependent and systemic. There is positive as well as negative feedback at play, and all actors, including governments, are constrained but also have some room to influence the course of development. Since the turn of the century, the prominence of sustainability transitions research has grown in line with an increased political attention to grand challenges such as climate change (IPCC, 2018, 2014) and biodiversity loss (IPBES, 2019)).

Nevertheless, criticism has been raised that sustainability transitions research is not sensitive enough to the diversity of potential directions within any broadly framed transition (Stirling, 2011). In the next section, we elaborate on the potential need for a more elaborate analysis of the direction of sociotechnical change, departing from ongoing debates within the field of sustainability transitions.

2.2. Sustainability transitions and the direction of change

As we have seen, transitions scholars are interested in fundamental shifts towards more sustainable patterns of production and consumption in society. These shifts are commonly conceptualized as the emergence, reconfiguration and decline of sociotechnical systems (Köhler et al., 2019). In studies based on the multi-level perspective (Geels, 2005, 2002; Rip and Kemp, 1998), which constitute one of the main strands of transitions research, the desirable direction of change is understood as a reconfiguration of entrenched sociotechnical structures referred to as regimes, and publications focus on exploring and conceptualizing the tensions and dynamics that characterize the underlying change process. A few contributions broaden the scope of inquiry to include attention to the multiplicity of more or less desirable sociotechnical configurations that may result from a transition. For example, Elzen et al. (2011) discuss normative orientations within transitions and Røpke (2012) explores how the formation of directions depends upon developments at the niche, regime and landscape levels. In general, however, the more specific characteristics of sociotechnical configurations are most often limited to references to "more sustainable" modes of production and consumption (e.g. from fossil to renewable energy).

In studies based on the technological innovation systems framework (Bergek et al., 2008a; Hekkert et al., 2007; Markard and Truffer, 2008), another main strand of transitions research, the desirable direction of change is rather expressed in terms of a focus on specific technologies which have desirable properties. Publications focus on the dynamics which propel the development and diffusion of such technologies but pay relatively little attention to the different trajectories these may follow. Although the topic is raised in studies that examine global innovation systems and spatial shifts in the emergence of industries and markets (Andersson et al., 2018; Binz et al., 2017, 2015; Binz and Truffer, 2017; Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015; Zhang and Gallagher, 2016), as well as the dynamics which underlie alternative technological trajectories (Hillman, 2008; Hojcková et al., 2018; Markard et al., 2009; Suurs and Hekkert, 2009), it has been argued that most studies nevertheless focus on one-dimensional diffusion of seemingly homogenous technologies (Yap and Truffer, 2018).

A more explicit integration of directionality with transitions-oriented analytical frameworks is made by Weber and Rohracher (2012), who suggest that innovation systems may exhibit "directionality failure". In the words of the authors, this "points to the necessity not just to generate innovations as effectively and efficiently as possible, but also to contribute to a particular direction of transformative change". The formation of directionality in innovation systems is further elaborated by Lindner et al. (2016), who highlight the importance of self-reflection, bridging and integration, anticipation, and experimentation, if innovation is to be guided towards desired ends. In a similar vein, Grillitsch et al. (2018) links directionality failures to characteristics of actors, networks and institutions, as key components of innovation systems. In addition, Yap and Truffer (2018) explores how directionality emerges as a result of functional processes in technological innovation systems. The directionality debate not only addresses the need for 'reflexive systems of innovation' that include components of guidance and self-moderation in innovation processes (Fogelberg and Sanden, 2008), but also resonates well with Churchman's point that the systems analysts themselves need to be critical and reevaluate the goal and boundaries set up for a study (Churchman, 1970), later framed as 'boundary critique' (Ulrich, 2003) or as the 'incumbency' of the transitions research community itself (Stirling, 2019).

Furthermore, the innovation policy literature, which to varying degrees overlaps the sustainability transitions field, has increasingly begun utilizing the concept of directionality to describe the desired effects of a new type of policymaking oriented towards tackling grand challenges rather than promoting economic growth. One prominent example is Mazzucato (2018, 2016), who argues for mission-oriented innovation policy where the state takes on a more active role in defining and promoting specific directions of economic change. In line with this general ambition, new analytical constructs are suggested, such as dedicated innovation systems (Schlaile et al., 2017) and mission-oriented innovation systems (Hekkert et al., 2020).[4] Another strand of the innovation policy literature focuses specifically on how policymaking can influence the formation of directionality. For example, Edler and Boon (2018) and te Kulve et al. (2018) link the direction of change to market conditions and discuss how policymaking may influence their characteristics in a way that shapes directionality towards desirable outcomes.

In contrast to the innovation policy literature, scholars such as Kuhlmann and Rip (2018) emphasize the role of non-state actors and collaborative governance when discussing sociotechnical change driven by grand challenges. This follows a line of inquiry from the first texts on 'transition management' (Rotmans et al., 2001), which focus on how to handle the *process* of change rather than on the *information* that can be used in the process. The approach acknowledges the many stakeholders involved in any transition and suggests suitable processes for establishing consensus on desirable directions of change (Kemp and Loorbach, 2006; Loorbach, 2010; Loorbach and Rotmans, 2010). However, relatively little attention is given to the actual directions and the various configurations they may result in.

Moreover, recent theorizing on deep transitions (Kanger and Schot, 2018; Schot and Kanger, 2018) makes more explicit references to directionality. As put by the proponents of this perspective, "a Deep Transition is formally defined as a series of connected and sustained fundamental transformations of a wide range of socio-technical systems in a similar direction. Examples of this directionality include a move towards increased labor productivity, mechanization, reliance on fossil fuels, resource-intensity, energy-intensity, and reliance on global value chains" (Schot and Kanger, 2018, p. 1045). This framing of directionality bears clear resemblance to Nelson and Winter's ideas on industries following certain 'natural trajectories' (Nelson and Winter, 1977, p. 58).

Lastly, Stirling (2011, 2009, 2008) is a clear voice pointing out a slightly different implication of directionality. Arguably, he introduced the concept to the field of sustainability transitions research, as part of broader critique of one-dimensional growth ideology. In line with a multidimensional view on sociotechnical change, he stresses that innovation is better viewed as "a vector, rather than just a scalar quantity" (Stirling, 2011, p. 84, 2008, p. 263). But he goes further and makes a passionate and eloquent call for a more pluralistic perspective on technological innovation. The result is an argument in favor of transparent and participatory governance processes, in order to highlight the contested nature of social and environmental objectives, and to manage issues of power, conflict and representation. The task of transitions studies is hence as much a process of 'opening up' a space of alternative directions, as one of 'closing down' and support development in specific directions (Stirling, 2011, 2008). In fact, and as recently pointed out by Stirling (2019), common transitions concepts such as 'regime' or 'levels" may risk strengthening prevailing perceptions and lock-ins, and thereby hide important power relations instead of exposing them to scrutiny.

By including not only the plurality of views but also elements of power and coercion, this viewpoint is in line with critical systems thinking (Jackson, 2001). Pel et al. (2020) build on these insights in an analysis mapping how actors involved in a transition relate to three aspects of directionality: sociotechnical multiplicity (which technological configurations exist in the minds of actors), diversity of appraisal (what 'performance criteria' or values guide different actors), and diverging process dynamics (which transition pathways are envisioned). They further elaborate on how a transition characterized by such diversity can be governed, but pay limited attention to the multidimensional characteristics of sociotechnical configurations.

[4] See also Uyarra et al. (2019), Scordato et al. (2017) and Pigford et al. (2018) for slightly different perspectives.

2.3. Unpacking direction in the directionality of technological innovation

The previous section shows that the sustainability transitions literature represents an important step away from the historical understanding of innovation as a one-dimensional phenomenon and is aligned with traditions that acknowledge normative as well as positive directionality of technological innovation. Conceptual frameworks and empirical investigations focus on specific directions of change, rather than general expansion of economic activity. And a growing body of knowledge provides important insights into the formation of directionality as well as about how it can be influenced by policymakers and other actors. Some studies also explicitly acknowledge the multitude of perspectives, interests and power of different stakeholders that influence or are influenced by the direction of change.

However, while the literature engages with the formation of specific trajectories, it largely fails to conceptualize and, in any detail, elaborate on the differences between trajectories. In most cases the distinction between alternative directions is not analytically clear. This reduces the value and applicability of the literature in processes of sensemaking and governance.

This lack of clarity regarding what must be a central element in discussions on directionality makes us take a step back from pathways, dynamics, causal explanations, governance and participatory processes, and instead search for distinguishing characteristics of the directions themselves. If innovation, in Stirling's words, is a vector rather than a scalar quantity, this vector needs to exist in an n-dimensional space. And in order to support efforts to describe and shape sociotechnical change, this space needs to be unpacked and conceptualized.

Our ambition here is thus modest – we aim to start a discussion on the dimensions of such a sociotechnical solution space. Inspired by the early work of Zwicky on 'the morphological approach' (Ayres, 1969; Foray and Grübler, 1990; Jantsch, 1967; Ritchey and Arciszewski, 2018; Zwicky, 1967), and the concept of 'design space' (Stankiewicz, 2000), we thus seek to initiate the development of a more elaborate *morphology of sociotechnical systems,* or put differently, an understanding of the configurations which may emerge as a result of technological innovation. However, we broaden the scope from the more narrowly technical space suggested by Zwicky, to a sociotechnical space, by building on the rich literature on sociotechnical systems that has developed over the last half century. We thus stay at the first step in the framework developed by Pel et al. (2020), and further explore what they call sociotechnical multiplicity.

A better understanding of the sociotechnical solution space can potentially inform investigations of several sorts. Prospective studies may investigate which directions that are *possible,* given logical or physical constraints; *likely,* given identified drivers, barriers and dynamics (positive directionality); or *desirable*, given different kinds of appraisal and normative stands (normative directionality). Similarly, retrospective studies may investigate the historical shaping of sociotechnical systems and speculate on counterfactual outcomes (Cowan and Foray, 2002).

While our strategy is purely analytical, we imagine that this type of morphology can be useful also in participatory processes. In fact, in comparison to adopting configurations proposed by stakeholders as objects of study, starting from first principles and possible futures could reduce problems related to bounded rationality and skewed power relations. This follows a cardinal idea of de Jouvenel's 'futuribles' (de Jouvenel, 1967); in the words of Jantsch (1967, p. 92): "The best available means of avoiding this dangerous imprisonment within a restricted outlook is the systematic creation of feasible anticipations which represent possible futures or 'futuribles'". A related idea of how to escape too limited views on future directions have been put forward and framed as backcasting (Holmberg and Robert, 2000; Robinson, 1982). We find in our own experience from working in the field of innovation, technology assessment and futures studies that there is an emancipatory force in starting with theoretical speculation of the possible, and thereby to some extent avoid the prison of the present and strong voices of powerful actors. While this does not fully guard against prejudice and bounded rationality (Stirling 2019), an explicit categorization exposes the analysis to fruitful criticism and a more precise discussion on shortcomings. We believe the creation of an explicit space of possibilities can be used to 'open up' discussions, to include directions that otherwise would have been disregarded (Pel and Boons, 2010; Stirling, 2008).

Finally, an explicit and more fine-grained morphology of sociotechnical systems could potentially help bridging the gap between the scientific communities focusing on innovation and technology assessment. These communities emerged as interlinked fields with a common interest in management and governance of technology (Ayres, 1969; Coates, 1972; Jantsch, 1967; Porter et al., 1991). However, while concepts such as 'transition management' and 'transition governance' (Kemp and Loorbach, 2006; Rotmans et al., 2001), 'constructive technology assessment' (Schot and Rip, 1996), and 'responsible innovation' (Owen et al., 2013), indicate remaining links, and observations are made of a new wave of interest in 'technology foresight' and 'technology roadmapping' (Banse et al., 2011; Georghiou et al., 2008), most research on the dynamics and consequences of technological innovation are developing as separate disciplines (Green and Randles, 2006; Sveiby et al., 2012). As a result, the sustainability transitions community approaches transitions with a strong focus on processes of change, while paying less attention to the multiplicity of potential outcomes. Conversely, much of the assessment literature starts with some given, often quite detailed, description of a technology, product or production system, and then elaborates on its effect on a property of its environment, such as climate change or unemployment rates. Some methodologies, such as consequential life cycle assessment, attempt to include a causal link between impact and system intervention, but the applied analytical frameworks seldom go beyond economic equilibrium models (Ekvall and Weidema, 2004), and fails to account for the rich dynamics explored in the innovation and transitions literature (Sandén and Karlström, 2007). While disciplinary specialization is inevitable and to some extent desirable, a stronger link between analyses of the dynamics and consequences of technological innovation is clearly needed in a world which calls for rapid change of large and complex systems of production and consumption and where goals are not only contested but also multidimensional. In the remaining parts of this paper, we attempt to contribute to this link by outlining the contours of a morphology of sociotechnical systems.

3. Towards a morphology of sociotechnical systems

3.1. Technological innovation as the transformation of sociotechnical systems

Technology can be defined as a collection of artifacts and knowledge that perform a function (Arthur, 2009), or as put by Heidegger, as "an ordering of the world to make it available as a "standing reserve" poised for problem solving and, therefore, as a means to an end" (Heidegger, 1977, p. 19). This implies that a technology can be specified narrowly or broadly, covering everything from a minor technical component to an entire economic sector. In the sustainability transitions community, however, technology is most often discussed with respect to a function embedded in a reasonably complex focal product. For example, wind power technology is associated with a wind turbine that converts winds to electricity.

When adopting a dynamic perspective, it is evident that the development and diffusion of a technology brings changes beyond the artifacts and knowledge that are immediately associated with the focal product. Any product is created through processes that combine components, sub-systems and other inputs, and it is also used in processes that combine it with other products to perform different functions (Arthur, 2009). A wind turbine is created by combining a tower, generator and propeller, while the electricity it produces is distributed through power lines to be used in various electrical appliances. Technological innovation accordingly involves not only the development and diffusion of a product, but rather the emergence of value chains that combine artifacts and knowledge in interlinked processes of production and consumption (Sandén and Hillman, 2011).[5]

Moreover, this is associated with organizational and institutional change. As a technology develops and diffuses, firms and consumers enter different parts of the emerging value chain, while universities, government agencies, civil society organizations and other actors may engage with, and adapt to, the new processes of production and consumption. This also leads to and requires changes in institutions such as public laws and regulations, industry standards and routines, and individual attitudes and beliefs (Branscomb, 1973; Geels, 2002; Hughes, 1987).

To capture the results of technological innovation, it is therefore appropriate to use concepts that highlight a broad range of social and technical elements. One such concept is the commonly used notion of sociotechnical systems of production and consumption, which describes how heterogenous elements, such as artifacts, knowledge, actors and institutions, interact in order to create and use a specific product (Bergek et al., 2008b; Coenen and Díaz López, 2010; Geels, 2004).[6] As innovation processes propel a technology throughout its lifecycle, an associated sociotechnical system expands (and eventually contracts). At the same time, sociotechnical systems that capture production and consumption activities based on other technologies may decline or transform.

Given the many types of components of such systems it is evident that no matter how one defines a technology there will be a multitude of sociotechnical configurations that could serve to fulfil its function. Technological innovation is therefore not a one-dimensional phenomenon, even though conventional s-curves used to illustrate technology lifecycles may suggest so. Technological innovation can follow different trajectories, which not only result in different levels of diffusion of a focal product, but also give rise to different configurations in the related sociotechnical system. Fig. 1 illustrates this reasoning by showing six potential development trajectories. Trajectories A, B and C result in a high level of diffusion, but the sociotechnical configuration differs. Similarly, trajectories D, E and F result in a low-level diffusion, but different sociotechnical configurations. In contrast, trajectories A and D, B and E, and C and F, respectively result in similar configurations, but different levels of diffusion.

We may now make a distinction between the pace and the direction of innovation: the pace of innovation processes determines the level of technology diffusion (size) and thus captures general expansion and growth; while the direction of innovation processes determines the multidimensional configuration (shape) of an associated sociotechnical system.

To analyze and discuss the directionality of innovation, both from normative and positive perspectives, it is not sufficient to conclude that various configurations are possible. There is also a need to explore the characteristics of these configurations. In the next section, we will take the first steps towards such a morphology of sociotechnical systems, by deducing a set of fundamental dimensions from first principles.

3.2. Three fundamental dimensions of sociotechnical systems

At the outset, we need to make clear that there are two types of boundaries of relevance for a morphological analysis. First, we need boundaries that define the analytical space in which an investigation takes place, simply because is impossible and seldom relevant to investigate the whole universe. Second, we are interested in describing (or prescribing) boundaries that define the shape of one or

[5] Observe that a value chain is also a means linked to an end and therefore constitutes a technology in the broad sense used here. Since the focal product also represent a technology, such as the conversion of wind energy to electricity, technologies are linked in hierarchies where the means of one are the ends of another.

[6] A system is commonly defined as "a regularly interacting or interdependent group of items forming a unified whole" (see for example the Merriam-Webster (2020)). The unified whole is often interpreted as a function or purpose. Importantly, the idea of a system purpose neither implies that the system is "conscious" and has a "will", nor that its components must share or even be aware of this purpose (Sandén et al., 2017). It simply means that for something to be viewed as a system by an observer, it needs to have one or several functions in its context. Observe that "context" does not necessarily mean a context physically outside of the system. A football club as a system may have a function for its individual members, but these individuals are much more than their membership, and as full human beings they are thus part of the context and as such appreciate the function the football club has for them.

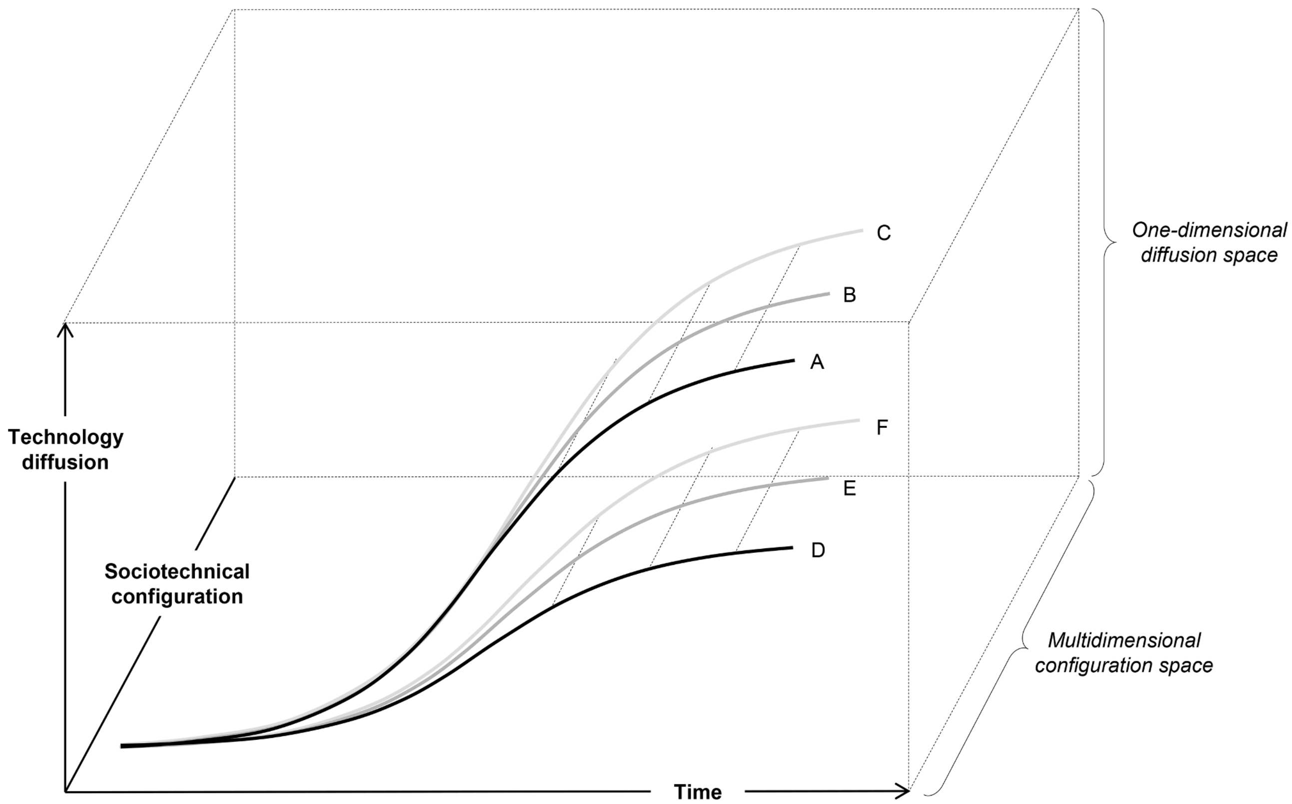

Fig. 1. Six potential development trajectories (A-F) for an emerging technology, resulting in different sociotechnical configurations and/or different levels of diffusion.

several sociotechnical systems within that analytical space. The analytical space can be defined by a few dimensions, which then also can be used to describe the shape of sociotechnical systems. In this paper, we suggest three fundamental dimensions, the temporal, spatial and sociotechnical (Fig. 2), and also utilize that the latter can be further decomposed into several subdimensions.

As described in Section 3.1, our primary analytical focus is technological innovation. Hence, our primary analytical boundaries are set in the sociotechnical dimension, where we define the object of study as a system that captures the production and consumption of a focal product.[7]

The analytical boundary in the sociotechnical dimension can be broad or narrow but is always derived from the definition of a technology as means to an end, and thus departs from a generic value chain (Fig. 3). This generic value chain has a horizontal and a vertical dimension, and to define our analytical interest we need to set boundaries in both. The horizontal breadth denotes the range of *alternative value chains*. If we define our interest broadly as "transportation" we include all imaginable value chains that deliver the function of transportation. Within this space we can then study realized, foreseen, or hoped for sociotechnical systems producing and consuming transportation. If we instead delimit our interest to "electromobility in the road freight sector", we have narrowed down the range of included alternative value chains by further specifying some means and ends. Due to the interconnected nature of reality, such value chains in principle expand infinitely in the vertical dimension, from ultimate means to ultimate ends. Which complementary production and consumption steps to include in a specific sociotechnical system is therefore a matter of vertical boundary setting, which effectively means cutting off *complementary value chains*. In the example above one may, for example, want to include truck manufacturing and the production of truck batteries, while excluding steel production, manufacturing of the machines used to produce trucks and the production of generic knowledge in electrochemistry.

The temporal and spatial boundaries of an investigation may be implicit but are always there in practice, since it is impossible to cover the entire history and complete future or all imaginable, and unimaginable, regions of the universe (Sandén et al., 2017). Distinctions can be made between retrospective studies, describing the past, and prospective studies, envisioning or prescribing alternative futures, and between studies with different spatial scopes such as global, national or local. One could also, in comparative studies work with two or more analytical subspaces to compare the shape of certain sociotechnical systems within these.

We also need to observe that besides these "outer" analytical boundaries, which excludes parts of the universe from our investigation, there are also "inner" analytical boundaries, which define at what level of granularity we seek to describe shapes. Studies of sociotechnical systems are, for example, seldom concerned with changes taking place at the timescale of nanoseconds or over distances of millimeters, nor with the smallest parts of machines and only sometimes with individual human beings. Nevertheless, choices are made between days and decades, counties and countries, and firms and industries. In the following we will not discuss this fractal character of the dimensions used to describe the shape of sociotechnical systems, but do not preclude this from being an interesting topic for future work on sociotechnical morphology. However, the descriptions of sociotechnical configurations in the next section utilize that the sociotechnical dimension can be described in terms of different types of components; the technical part in terms of matter and knowledge combined into artifacts and processes, and the social in terms of actors and institutions (Bergek et al., 2008b; Geels, 2004; Hughes, 1987; Rip and Kemp, 1998; Sandén and Hillman, 2011; Wieczorek and Hekkert, 2012).[8]

3.3. Configurations of sociotechnical systems

In the previous section, we identified three fundamental dimensions that give rise to the space in which sociotechnical systems may adopt different shapes. Our focus now turns to the characteristics of these shapes as we describe system configurations from technical, social and spatial perspectives. We accordingly start with the dimensions discussed above but distinguish between a technical and a social part of the sociotechnical domain. We also choose not to explicitly elaborate on configurations related to the temporal dimension. All sociotechnical systems certainly exist in time with more or less distinguishable starting and end points, and in between they may take different development paths. However, as an analytical perspective, the temporal dimension is relatively simple and therefore appears in the examples in Section 4 in combination with the other dimensions without any further elaboration on 'temporal shapes'.

As described above, we take an analytically defined sociotechnical system as our starting point. This system captures a function related to a given technology, conceptualized as a generic value chain with horizontal and vertical extension, but may nevertheless adopt different configurations (that describe different ways in which the system function can be realized). As an overarching organizational principle in our effort to unpack these configurations, we make the simple distinction between many and a few, and elaborate on scales from distributed to concentrated, from diverse to standardized, and so forth. This simple distinction between many and a few will return repeatedly as we elaborate on the characteristics and properties of technical, social and spatial configurations, respectively.

3.3.1. Technical configurations

Technical configurations emerge from the characteristics of and relations between artifacts and processes in sociotechnical systems,

[7] Alternatively, one could have started with, for example a spatial boundary, and study sociotechnical structures within this boundary as is done in various forms of regional studies, or what an actor, or group av actors do, which is the typical strategy applied in organizational studies.

[8] It is also possible to expand the domain covered by the system to include not only social and technical components, but also the geological and ecological components that make up the natural environment. Bringing such socio-techno-ecological analytical perspectives into sustainability transitions research has been called for by among others (Ahlborg et al., 2019).

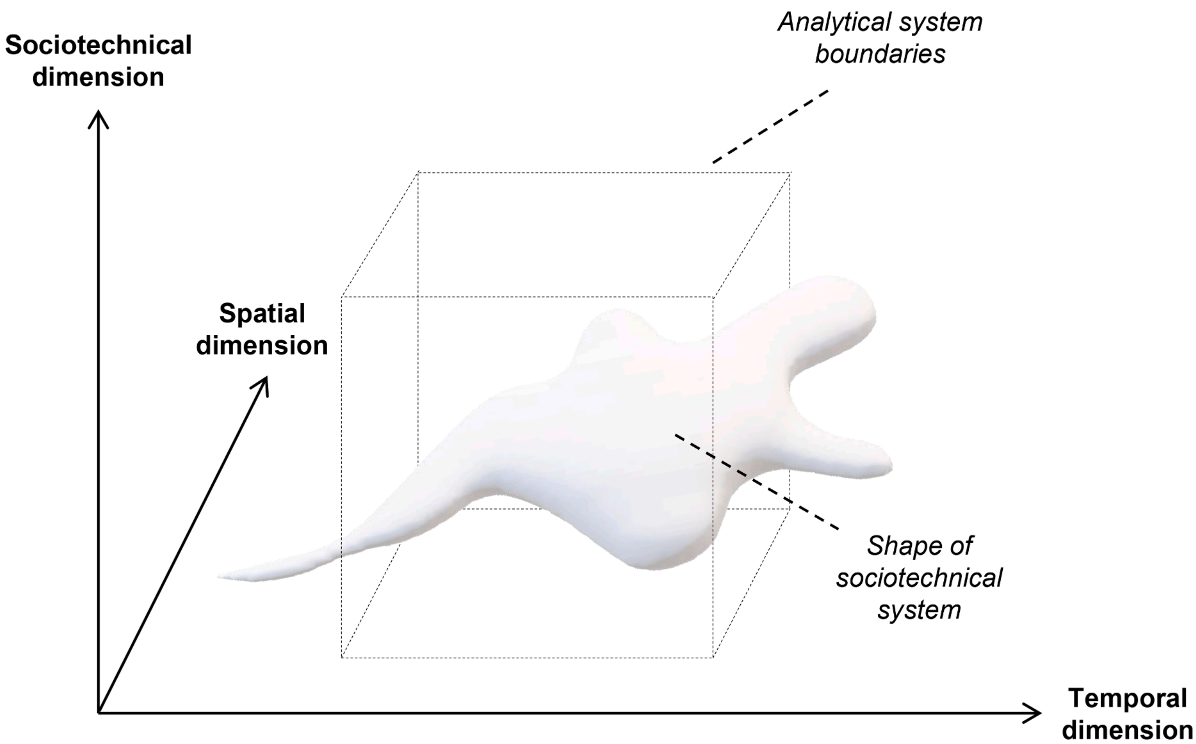

Fig. 2. Three fundamental dimensions that define a space used to set analytical boundaries and describe the shape of sociotechnical systems.

sometimes captured by the terms technologies and techniques, or even more fundamentally by energy and matter and the knowledge of how to organize these to convert means to ends. In the following, we highlight six different properties of technical configurations.

First, as thoroughly elaborated in life cycle assessment studies (European Commission - Joint Research Centre, 2010), the *types of technical components* (i.e. energy, materials and processes) used will determine the physical flows crossing the analytical system boundary, which leads to different environmental effects. Solar cell technology can for example be based on different materials such as silicon or cadmium telluride, and the production and consumption of these will influence problems such as resource scarcity and toxicity in different ways.

Second, technologies such as solar cells, textiles or transport can be realized by many or few alternative value chains at the same time. If there are many there is a high degree of *technical diversity*, and if there are few we may instead refer to a high degree of *technical standardization*. Technical diversity is thus a concept that captures the number of alternative value chains that are qualitatively different across the horizontal axis, and this can be measured at any vertical level (see Stirling 2010 for a more detailed account of diversity).[9] Notably, this is a well-acknowledged factor in the literature on evolutionary sociotechnical change. Technically diverse systems may be preferable in early development stages where there is a need to experiment with different solutions, while more standardization is called for in later development phases since it tends to bring lower costs through economies of scale. As observed by Abernathy and Utterback (1978), increasing standardization is a defining feature of technology lifecycles.

Third, there can also be many or few alternatives that are qualitatively similar but physically separate. Electricity production (as an analytically defined technology) could for example be accomplished by a few large nuclear plants or by millions of small solar cells. This implies a property of *physical concentration,* or conversely, *physical distribution*. The level of physical concentration may have an impact on system control and resilience. Note also that the level of physical concentration can vary across the vertical axis of the value chain; for example, the millions of solar cells in the example above may be produced in a few large factories.

Fourth, along the vertical axis there can be many or few distinguishable process steps that rely on different techniques or knowledge domains, and hence we may distinguish between configurations that have a high degree of *technical specialization,* or the opposite, a high degree of *technical integration.* As a sociotechnical system grows, there is often a tendency towards higher degrees of specialization. This property relates to the modularity of a technology, and hence to positive aspects such as cost reduction, speed of development, problem identification, flexibility and resilience (Simon, 1962), but also to risks of loss of oversight and missed opportunities to increase efficiency by process integration.

9 Stirling (2010) is more elaborate in terms of formally outlining varieties of technical diversity. Focusing on value chains and their constituting sociotechnical components, as suggested here, may potentially have some additional merits in identifying technological distance and diversity in discussions on competition and coevolution (see also Sandén and Hillman 2011 on sociotechnical overlaps).

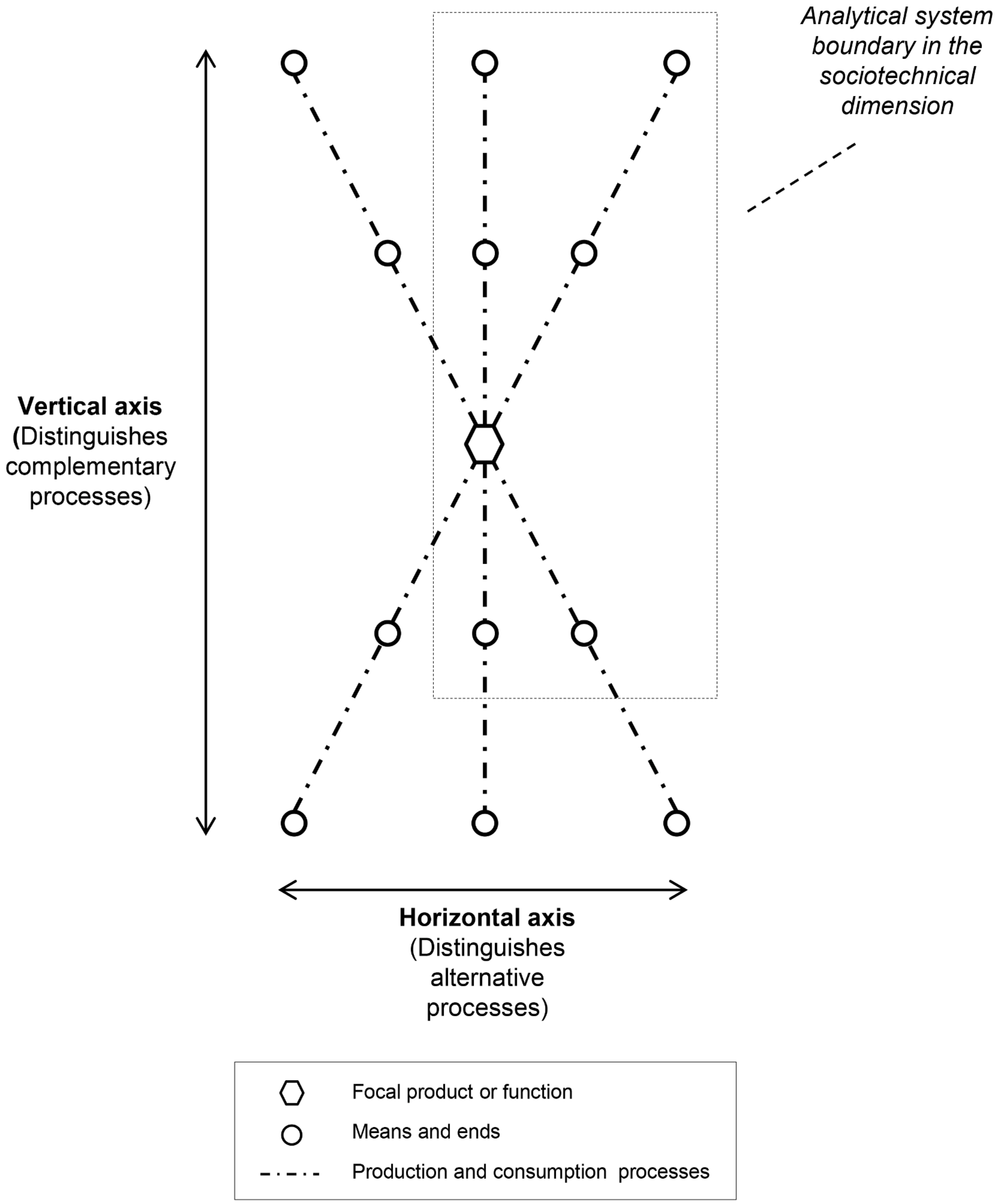

Fig. 3. A generic bundle of value chains that combine means and ends to produce and consume a focal product or function. In this illustration, an analytical system boundary in the sociotechnical dimension has a horizontal breadth that excludes some alternative processes and a vertical extension that excludes some complementary downstream consumption processes.

Fifth, the vertical extension of the value chain can also be *physically integrated* or *physically separated*, that is, the value chain may be more or less integrated in one artifact or distributed between physically separate entities. Things that we normally consider to be an artifact can in fact be viewed as a physically integrated and largely automated value chain, such as the wind turbine converting the energy in moving air masses to electricity. But also more extensive value chains can have high degrees of automation, in the sense that processes are seldomly interrupted by human decision making. There are of course numerous potential impacts of moving towards more, or towards less autonomous technologies.

Finally, empirically observed systems may in the formative phase, before production and consumption is fully materialized, lack components and process steps in the vertical chain. We can thus distinguish between different levels of *completeness* (or *incompleteness*), a configurational property which is of course correlated with system growth and maturity. Incompleteness may, however, also be observed for mature systems due to narrow system boundaries in other dimensions (see Section 3.3.4).

3.3.2. Social configurations

Social configurations describe who is involved in a sociotechnical system and how they interact, or in other words, how human agents are coordinated through different forms of organization and institutional arrangements. Without any ambition of being exhaustive, we here provide some examples of social configurations.

To begin with, as with technical components, the generic value chain can be populated by different *types of social components*. These include various actor types such as consumers, firms, universities, government agencies and civil society organizations, and different institutions ranging from informal norms and beliefs to formal laws and regulations. The types of social components can of course result in a vast number of desirable and undesirable effects. Recent examples that have received attention include observations of child labor in cobalt mining in electric vehicle battery value chains (Sovacool, 2021) and concerns for forced labor in silicon solar cell value chains (Swanson and Buckley, 2021).

Furthermore, there can be many or few actors, connected in different ways across the horizontal dimension of the value chain. A system may be dominated by a few large firms or involve many smaller firms, which has clear implications for economies of scale, resilience and competition. We will refer to this property as the level of *operational concentration*, or conversely, *operational distribution*. A related but separate property relates to ownership. This is important since it largely determines strategic orientation and distribution of profits and losses. One may distinguish different kinds of ownership (involving different types of actors such as private or public organizations), but also focus on whether there are many or few owners. We will refer to the latter property as the level of *ownership concentration*, or conversely, *ownership distribution*. Notably, high levels of operational or ownership concentration corresponds to systems characterized by monopolistic or monopsonistic markets.

Similar but distinct properties can be identified in relation to actors across the vertical dimension of the value chain. Many separate actors lead to a high degree of *operational specialization*, while few separate actors imply a high degree of *operational integration*. We may also distinguish between *ownership specialization,* or conversely, *ownership integration*. It should be noted that the notion of a vertically integrated company corresponds to a situation where a large part of the vertical extension of the value chain is covered by one firm.

Organizing a value chain within one company, where individuals are coordinated hierarchically via employer-employee contracts, or between many companies that interact more flexibly on markets without sharing any other information besides price and performance of the goods that is exchanged, constitute two extreme forms of actor interaction. Other varieties of information sharing open for intermediate forms, often captured by the term “network” (Powell, 1990). Across the vertical axis of the value chain, information may be shared in supplier-customer networks, which has proven important for innovation (Bergek et al., 2008a; Carlsson and Stankiewicz, 1991; Håkansson 1990; Jacobsson et al., 2004). Horizontally, positive externalities, such as knowledge spillovers and other shared system elements, may in some cases lead to faster development (Bergek et al., 2008b; Sandén and Hillman, 2011), but in others slow down development due to reduced incentives for private actors to invest. The level of operational concentration and integration, discussed in the previous paragraphs, is thus not only qualified by the number of firms but also by the extent to which networks and other ways of sharing assets are present.

Finally, while the discussion above focuses on the number of and relationships between actors, we could also discern properties that are primarily institutional. People can, for example, view our analytically defined generic value chain as one coherent system, with a clear function conceptualized in one or a few words, or have very different views on the purpose and role of different system elements, and maybe even lack words describing the whole. Systems may thus differ with regards to the level of *cognitive alignment* (or *misalignment*). Similarly, people can be more or less in agreement regarding the desirability of the value chain (in relation to other technologies) and what future development scenarios that are preferable. The extent to which actors agree on such matters may be referred to as the level of *normative alignment* (or *misalignment*). If there is some normative alignment, the perceived value, or legitimacy, of current states and future possibilities may certainly differ as well. In addition, actions undertaken by actors can be subject to different levels of *formal regulation* (or *deregulation*). Policy interventions in the form of technology specific laws and regulations are arguably necessary for the function of any sociotechnical system, and particularly for shaping its diffusion in desirable directions. But excessive regulation may also slow down technological innovation and lead to various inefficiencies in processes of production and consumption.

3.3.3. Spatial configurations

Spatial configurations describe how a sociotechnical system is localized in (geographical) space. One could argue the spatial dimension should be handled as an institutional dimension, since what matters most with regards to location may be the jurisdictions (i.e. states or countries) covered by a value chain, which in many cases also coincide with spatially bounded national cultural identities. Alternatively, one could focus on the physical aspects, such as the distances in kilometers or the different natural environments a value chain would cover. Given the remarkable importance given to area bound jurisdictions by human society over the last thousands of years we will here mainly treat the spatial dimension as a matrix of countries or regions, while acknowledging that there are numerous other important aspects of spatial localization.

When it comes to localizing sociotechnical systems in the spatial dimension, it is admittedly easier with more tangible components such as factories, while it is less straightforward for intangible components such as firms, knowledge and institutions. Nevertheless, it is possible to at some, and most often sufficient, level localize intangible components as well. For example, we may point to the jurisdictions in which regulations are enacted or the physical representations of firms in the form of people and artifacts.

Depending on the perspective of the observer, some *types of spatial localization* are clearly more desirable than others. For example, a policymaker that represents a particular country, or a trade union, is likely to prefer that certain parts of a (desirable) value chain is located domestically, rather than abroad.

In addition, we can derive properties that are similar to the ones discussed with respect to technical and social configurations. A value chain may extend horizontally over many or few regions (i.e. similar products are produced or consumed in many or few regions), which we refer to as level of *regional concentration* (or *distribution*). While regional concentration tends to bring economies of scale or intensified learning through network effects in regional clusters (Marshall, 1890; Porter, 1990; Saxenian, 1996), it can also be argued that regionally distributed systems are more resilient. Across the vertical axis, the value chain may also cover many or few regions, which corresponds to the level of *regional specialization* (or *integration*). Regionally specialized systems, such as when production steps are spread out over a global supply chain, are often characterized by high cost-efficiency, but at the same time extensive interdependence may bring risks of supply or demand interruption in case of international conflicts or trade wars. Shorter distances between suppliers and buyers could also facilitate knowledge sharing in close supplier-customer networks (as discussed above) and thus speed up innovation. However, to the extent that this comes with less interaction with actors in other regions, it may bring higher risks of missing out on important global trends.

3.3.4. Multidimensional configurations

Technical, social and spatial configurations can be combined in different ways into more complete multidimensional shapes of sociotechnical systems, and these may be combined with the temporal dimension to describe how they change over time.

Although technical, social and spatial configurations represent logically separate (orthogonal) dimensions, they are often causally related. For example, a technical configuration that involves a production process which converts virgin raw materials to some product, will by necessity bring a spatial configuration in which the system is present in a region where these raw materials are available.

We also need to observe that the choice of analytical boundaries in one or several dimensions can affect the observed configuration in another. As was noted above, technical incompleteness can be the result of a narrow temporal boundary (if a system is not completed within the observed time-period). Similarly, if the spatial boundary of a study delimits the observed space to a single country, or anything smaller than the world, global specialization may lead the system to appear incomplete to an observer; and if the analytical boundary in a sociotechnical dimension restricts the field of observation to a limited set of artifacts or actors, parts of the value chain may also disappear from the view of the analyst. This phenomenon does not only affect completeness but also other properties. Observed high ownership concentration could for example be the result of narrow spatial or sociotechnical analytical boundaries.

In the preceding sections, we have unpacked some important characteristics and properties of technical, social and spatial configurations, which are summarized in Table 1. However, challenging work remains to develop a more detailed morphology of sociotechnical systems. In technical, social and spatial dimensions, the identified configurational properties could be explored further, while additional properties may also be added to the conceptual framework. In addition, there could be efforts to identify generic techno-social, techno-spatial, socio-spatial or techno-socio-spatial configurations, or perhaps even varieties of techno-socio-spatio-temporal shapes.[10] One should, however, be aware of that the selection of configurational properties for any empirical analysis or foresight exercise is as much an analytical choice as the selection of system boundaries (see Section 3.1), and should thus be subjected to reflexivity and boundary critique. While these tasks are left to future research, the next section illustrates the ideas presented so far, by providing three empirical examples focusing on technical, social and spatial configurations, respectively.

4. Examples of how a morphology may inform empirical investigations

The notion of directionality and the need to develop a morphology of sociotechnical systems has so far been discussed in relation to the existing literature and unpacked deductively. The focus of this section is to illustrate the presented conceptual ideas through empirical examples.

4.1. Example 1: Technical configurations of solar photovoltaics in Sweden

In a historical review of solar photovoltaics (PV) in Sweden, Andersson et al. (2021) show that the domestic market has grown steadily over the last 15 years. However, looking beyond market data reveals a development pattern that not only involves growth, but also stagnation and decline, albeit in different parts of underlying value chains. The case can thus be used to exemplify changing technical configurations over time. Based on Andersson et al. (2021), we compare the shape of the system in three time periods by following the development of different parts of the value chain (Fig. 4).[11]

Technically, the PV value chain can be defined from the production and use of PV modules. *Complementary* processes include upstream production of machinery, production of components (such as PV cells) and assembly of modules, downstream installation and use of modules, as well as various forms of research and development (R&D). A rough categorization of *alternative* upstream value chains differentiates between modules based on thin-film materials and silicon wafers. Downstream, modules may be used in

[10] Within the field of regional studies and geography of innovation there is for example a growing literature outlining techno-socio-spatial configurations (often focused on knowledge networks within and between regions, organizations and technological domains), drawing on quantitative data sources and network theory (see for example Balland et al 2015; Pintar & Scherngell, 2021). Attempts are also made to link such configurations to economic output (see for example Hidalgo and Hausmann, 2009).

[11] Due to the spatial analytical boundary drawn between Sweden and the rest of the world, the case also implicitly illustrates techno-spatial configurations.

Table 1
Summary of identified configurational properties.

Dimension	Configurational property	Description
Technical	Type of technical components	The specific characteristics of technical components such as energy, materials and processes used in the value chain.
	Technical diversity/standardization	The number of qualitatively different alternative processes across the horizontal axis of the value chain.
	Physical distribution/concentration	The number of physically separate alternative artifacts across the horizontal axis of the value chain.
	Technical specialization/integration	The number of qualitatively different complementary processes across the vertical axis of the value chain.
	Physical separation/integration	The number of physically separate complementary artifacts across the vertical axis of the value chain.
	Technical completeness	The extent to which the system includes all necessary complementary processes.
Social	Type of social components	The specific characteristics of social components, including various actor types and different institutions.
	Operational distribution-/concentration	The number of producing and consuming firms, or other organizations, across the horizontal axis of the value chain.
	Ownership distribution-/concentration	The number of owners across the horizontal axis of the value chain.
	Operational specialization-/integration	The number of producing and consuming firms across the vertical axis of the value chain.
	Ownership specialization-/integration	The number of owners across the vertical axis of the value chain.
	Cognitive alignment-/misalignment	The extent to which actors have a similar conceptual and qualitative understanding of the value chain.
	Normative alignment-/misalignment	The extent to which actors agree on the value, desirability and preferred future development of the value chain.
	Formal regulation-/deregulation	The extent to which actors are subject to formal policies in the form of laws and regulations.
Spatial	Type of spatial localization	The specific characteristics of how the system is localized in geographical space.
	Regional distribution-/concentration	The number of spatial regions involved in alternative processes across the horizontal axis of the value chain.
	Regional specialization-/integration	The number of spatial regions involved in complementary processes across the vertical axis of the value chain.

centralized applications, where modules are physically concentrated, in distributed on-grid applications where physically distributed modules are integrated via large electric grids, or in distributed off-grid applications, where small sets of modules function independently. Below we discuss the development of thin-film module production, silicon module production and module installation and use.

Academic research on thin-film modules started already in the 1980's and grew in size during the 1990s (Fig. 4, left part). This resulted in several university spin-out companies, and a few additional ventures were founded by entrepreneurs from industry. However, these actors struggled to mobilize the resources needed to establish commercial module production in Sweden. Instead, R&D mainly contributed to industrial development abroad as well as to some domestic commercial activities focused on supplying manufacturing equipment to international module producers (Fig. 4, right part). Other ventures continued R&D in thin-film technology but remained pre-commercial.

Although Sweden had no research on silicon modules, some production of these nevertheless started in 1992. A decade later, a few additional factories were established, and production grew rapidly, reaching an annual production level of 180 MW in 2008 and employing around 500 people (Fig. 4, center part). However, the Swedish factories were supplied with silicon cells from abroad and sold most of the output on foreign markets. This made Swedish module production vulnerable to international developments, and in 2010, Swedish production dropped sharply. The domestic industry disappeared completely in 2014.

While a small and stable market for off-grid applications had existed since the early 1990s, the installation of grid-connected modules did not take-off until 2006 (Fig. 4, left and center parts). After a decade of exponential growth, installed capacity had in 2018 reached 425 MW. The market is currently dominated by distributed on-grid applications, but since a few years the centralized segment is also growing rapidly (Fig. 4, right part). All market segments are mainly supplied by imported silicon modules. Research focused on the use of modules was initiated in the early 2000s, but activities remained limited until around 2010, when they increased substantially in connection to the growing Swedish market.

In conclusion, the evolution of the Swedish PV system has followed a development trajectory that involves dramatic changes in its technical configuration. Fig. 4 shows a shift from a focus on thin-film RD&D and small off-grid markets in the first period, to a rapidly expanding silicon module production in the second period, and, finally, to the disappearance of this industry and the rise of growing markets for grid-connected distributed and centralized installations in the third period.

The high level of incompleteness of the value chains in each period is partly caused by the early stage of development of the industry, but is even more a result of the spatial boundary of the analysis. Increasing regional specialization and concentration of silicon module production at the global level led to both the demise of Swedish silicon module production and the rise of installations based on inexpensive imported modules from China. The incompleteness, or fragmentation, of the Swedish PV system is amplified by a skewed technical diversity, or rather a high degree of standardization to different technologies in different parts of the value chain, with a research focus on thin-film technology and a production and application focus on silicon modules.[12] Andersson et al. (2021) argue that

[12] Admittedly, thin-film technology can be decomposed into subcategories based on different materials and knowledge areas, and hence, at this level, there is more diversity in Swedish PV R&D.

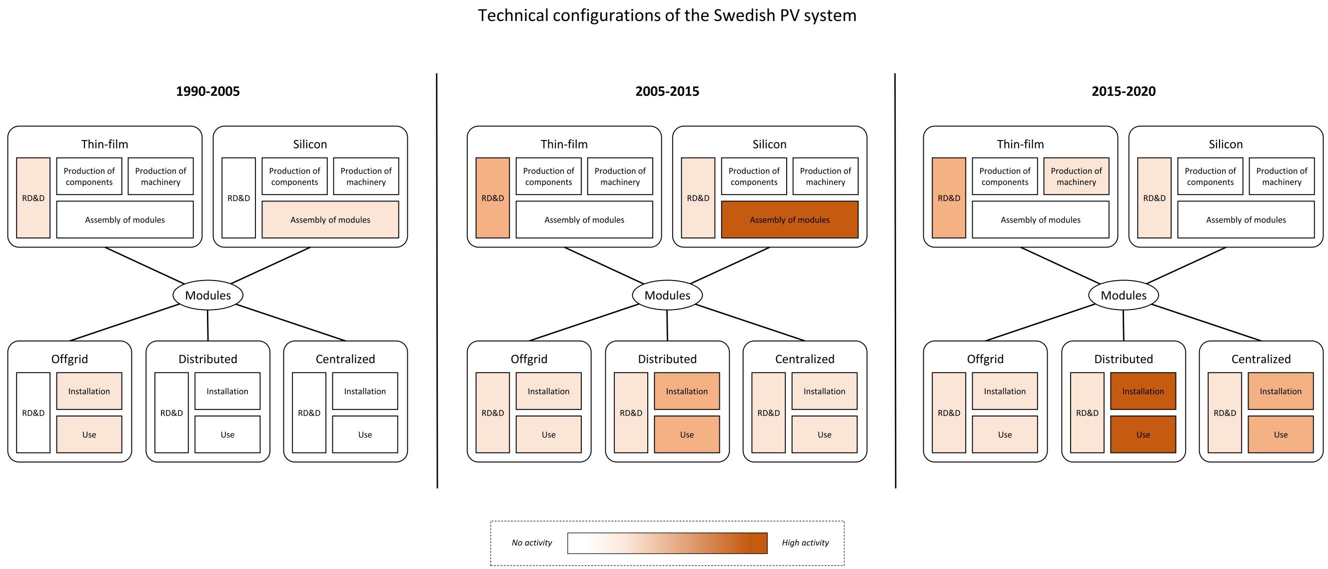

Fig. 4. Technical configuration of the Swedish PV system in three time periods. Based on Andersson et al. (2021).

these varieties of incompleteness and temporal mismatches might have harmed overall development of PV in Sweden.

Finally, the creation of domestic benefits has changed with the technical configuration. In the second period, the system created upstream employment and generated export revenues to the Swedish economy. In the third period, the system instead created downstream employment and contributed to renewable electricity supply for households and companies. Since these configurations correspond to different policy objectives, it is essential that directionality with respect to technical configurations is accounted for in efforts to promote the emergence of new technologies.

4.2. Example 2: Social configurations of electricity supply systems

If we stay in the area of electricity, but shift the attention to what in the previous section was viewed as downstream applications, we can discern different shapes of electricity supply systems and use these to exemplify not only technical, but also social configurations. Hojcková et al. (2018) present the future of the global electricity system as a choice between, or combination of, three alternative value chains for production and transmission of the focal product electricity (corresponding to the three application areas in the previous section): first, production centralized to a few large plants and transmission to consumers via an extensive grid; second, production distributed over a large number of plants and bidirectional electricity trade via a similarly extensive grid; and third, production distributed over a large number of plants with no or little grid-supported electricity transmission (i.e. off-grid production and consumption in households, companies or local microgrids).[13]

Going beyond the analysis of Hojcková et al. (2018), we observe that each of these alternative technical configurations can be combined with different social configurations. For illustrative purposes, we highlight two of the social properties discussed in Section 3.3.2, the level of operation and ownership concentration, and apply these to electricity generation. Distinguishing between concentrated versus distributed operation and ownership, respectively, leads to four social configurations whereof each in principle can be combined with each of the three technical configurations. Fig. 5 sketches the sociotechnical shape of the global electricity system as combinations of these twelve logically possible techno-social configurations at three points in time, 1990, 2020 and 2050.

Towards the end of the 20th century (1990), the global electricity system was dominated by production centralized to a small number of plants which were operated and owned by few actors, often state-owned electricity utilities (concentrated ownership and operation – large circle in Fig. 5, left part). A small amount of electricity was also produced in off-grid applications (distributed ownership and operation – small triangle in Fig. 5, left part).

Moving to 2020, a greater diversity of configurations have materialized, due to the opportunities brought by small-scale wind and solar power (Fig. 5, center part). While centralized production still dominates, some large wind and solar farms are owned by co-operatives (distributed ownership – small circle in Fig. 5, center part). In addition, many solar systems are owned and operated by private households and various organizations acting as prosumers, buying and selling electricity on the grid (distributed ownership and operation – medium-sized square in Fig. 5, center part). The distributed on-grid system also comes in other organizational forms, including leasing schemes (concentrated ownership and distributed operation – small square in Fig. 5, center part) and companies operating systems owned by households to balance the grid (distributed ownership and concentrated operation – small square in Fig. 5, center part). Finally, in parts of the world there exists leasing schemes also for off-grid systems (concentrated ownership and distributed operation, small triangle in Fig. 5, center part).

Looking ahead three decades or more into the future (2050), a great variety of configurations are possible. Fig. 5 (right part) outlines four examples. First, the upper-left diagram shows a highly concentrated system, possibly a variety of the 'global supergrid'. This represents a system that might be technically optimized, but also an oligopolistic, or even totalitarian future in terms of market power and resource control. Second, and in contrast, the lower left diagram illustrates a future where ownership and control are becoming increasingly decentralized, with many prosumers leaving the grid.[14] Third, the upper right diagram shows a 'smart grid' future, dominated by distributed ownership of small-scale on-grid systems; some operated by owners acting as prosumers, but many operated by professional firms offering grid balancing services. While these three futures all demonstrate a high level of standardization in that they gravitate towards a dominant techno-social configuration, the fourth scenario in the lower right corner illustrates a configuration with high techno-social diversity. Possibly, such a future hides interesting patterns in the spatial dimension, for example if different parts of the world are dominated by different techno-social configurations. All scenarios illustrate that even though there are links between configurations in the technical and social dimensions (a physically concentrated configuration must be centrally operated and is more likely centrally owned), multiple techno-social combinations are possible.

This case is limited to showing directionality with respect to social configurations in terms of owner and operator concentration at one vertical position in the electricity value chain (electricity generation). Alternatively, one could have explored social configurations in terms of, for example, vertical integration, diversity of actor types or cognitive alignment. Despite the limited scope, we hope the example still demonstrates the importance of considering alternative social configurations of sociotechnical systems, since these may have profound impacts on aspects such as distribution of resources and political power.

[13] Note that these system can be distinguished in terms of the level of physical concentration, where the centralized system has a high level of concentration of both production plants and grids, while the on-grid distributed system is concentrated in terms of grids but not production plants, and the off-grid system has a low concentration of both (many production plants and many grids). Note also that all systems are physically vertically integrated. See Hojcková et al. (2018) for details.

[14] While electricity production is distributed in this scenario, other parts of the value chain, for example production of solar modules and batteries could still be highly concentrated (as we saw in Section 4.1).

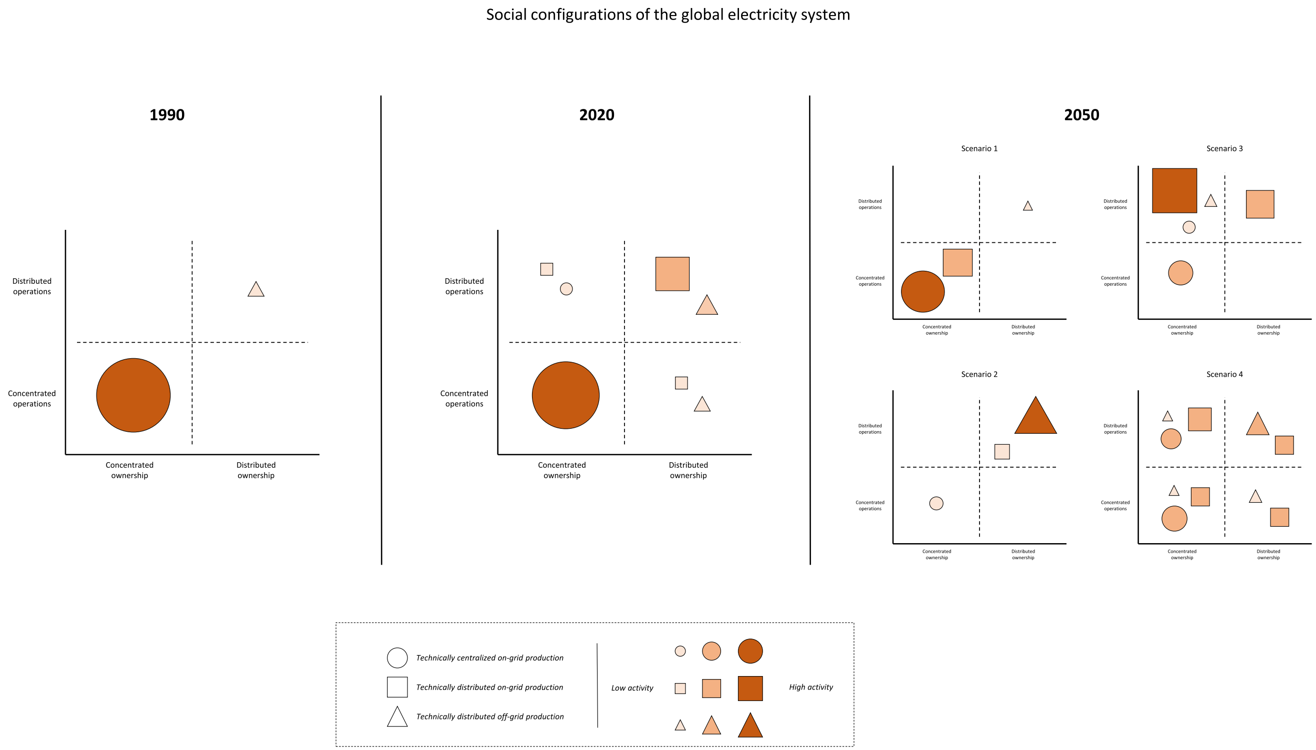

Fig. 5. Social configurations of the global electricity system in three time periods, 1990, 2020 and 2050. Elaboration on the three idealized technical configurations in Hojcková et al. (2018).

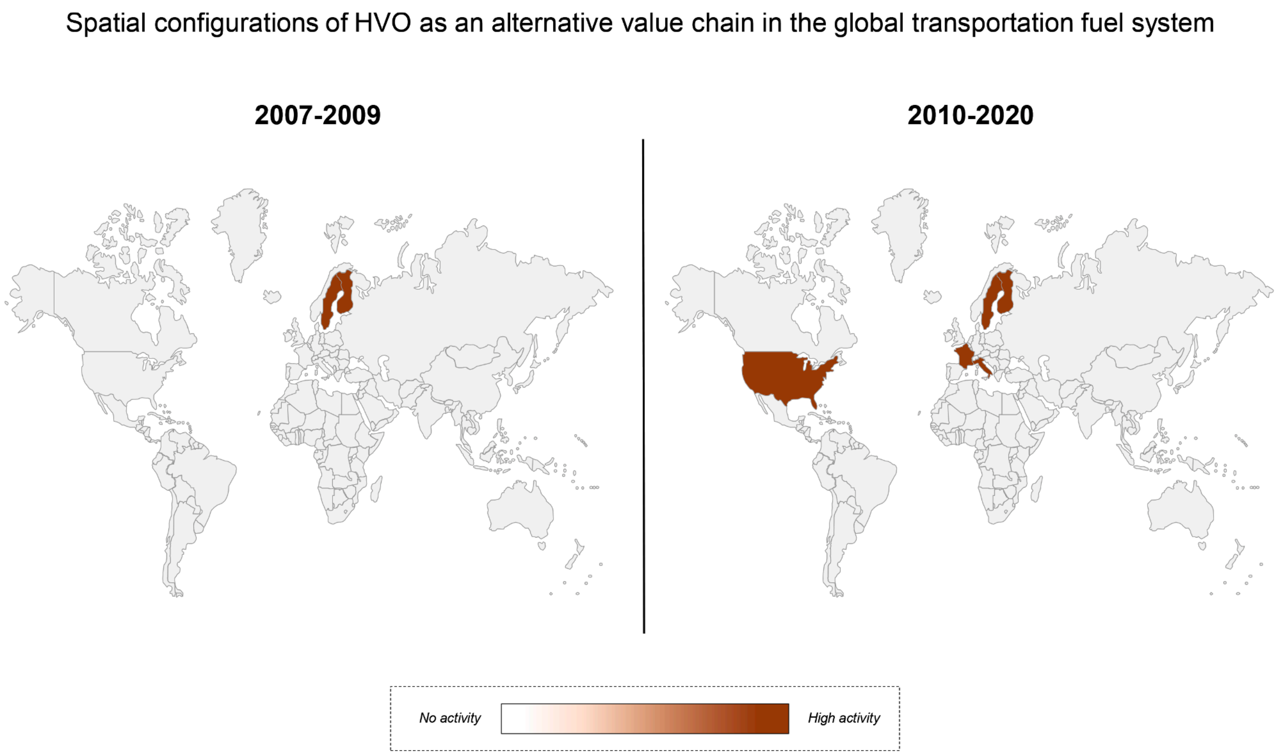

Fig. 6. Spatial configuration of HVO as an alternative value chain in the sociotechnical system for transportation fuels in two time periods. Based on Greenea (2017) and Kauppila (2018).

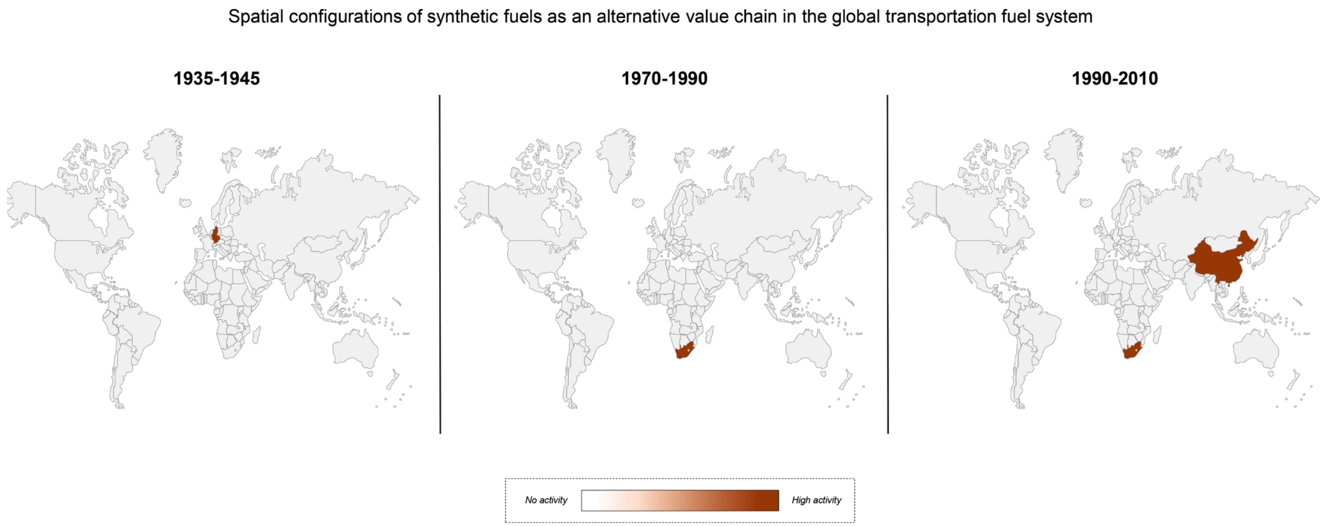

Fig. 7. Spatial configuration of synthetic fuels as an alternative value chain in the sociotechnical system for transportation fuels in three time periods. Based on GASIF (2007) and Higman and van der Burgt (2008).

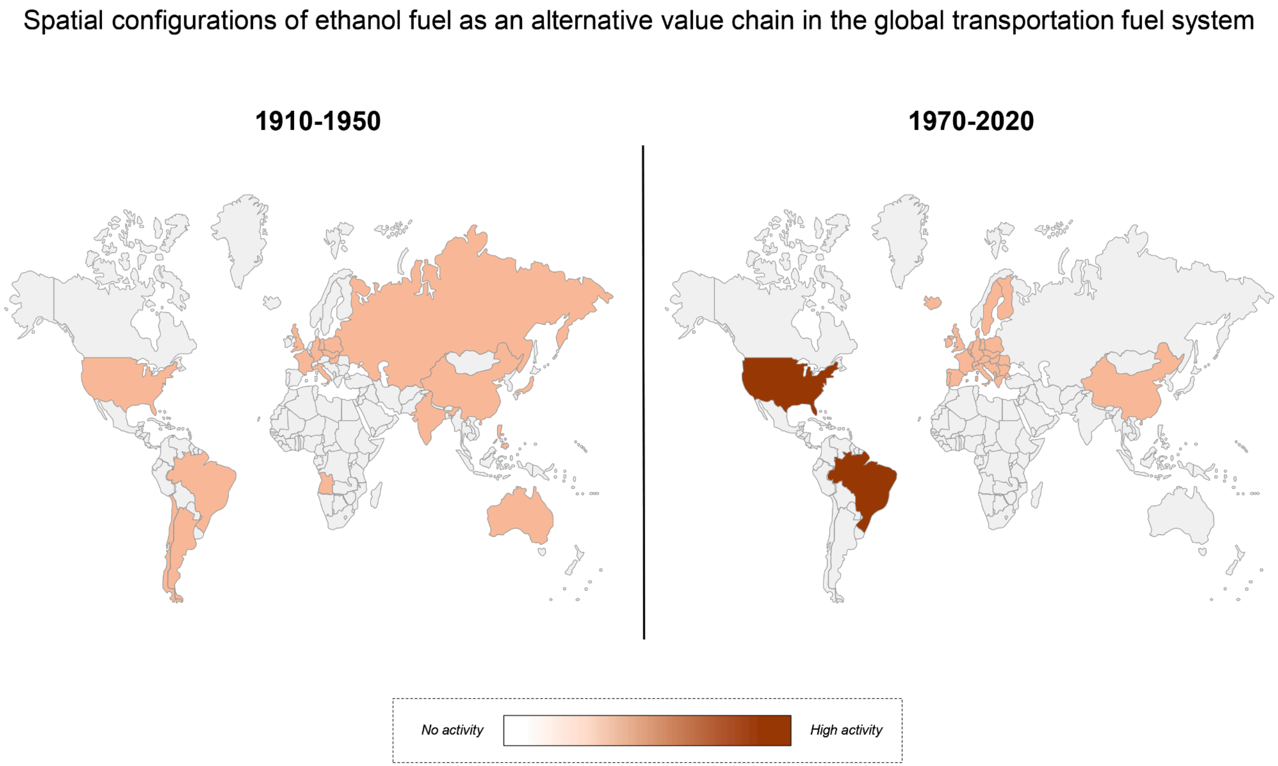

Fig. 8. Spatial configuration of ethanol fuel as an alternative value chain in the sociotechnical system for transportation fuels in two time periods. Based on EIA (2019).

4.3. Example 3: Spatial configurations of alternative transportation fuels

The global sociotechnical system for transportation fuels that can replace conventional gasoline and diesel based on crude oil, involves a number of alternative value chains that have developed along different spatial trajectories, and thus illustrate different spatial or spatio-temporal configurations. Drawing partly on an empirical investigation reported in Hellsmark and Hansen (2020), we here provide three examples.

Hydrogenated vegetable oil (HVO) development is a relatively recent phenomenon. It started in the early 2000s in response to an EU regulation mandating the use of renewable fuels and was in a first period spatially concentrated to Finland and Sweden (Fig. 6, left part). Since 2010, the production of HVO has spread to countries such as France, Italy and the USA, as a result of increasing demand for renewable diesel in Europe and an increasing global interest in renewable jet fuel (Greenea, 2017; Kauppila, 2018). This marks a shift towards a more regionally distributed system (Fig. 6, right part). While most produced HVO in the 2010s was consumed locally, an emerging international trade and the international sourcing of some feedstocks indicates a limited but increasing level of regional specialization. At the same time, a wide adoption of production methods developed in Scandinavia, indicates a high degree of technical standardization.

Diesel and methanol production from coal through thermal treatment, here called synthetic fuels, shows a different pattern, where regional integration, or more specifically, national integration of the whole value chain has been the dominating feature. The development and production of synthetic fuels started in Germany during the second world-war, which due to trade embargos had to come up with new ways of using domestic resources (i.e. coal) for producing transportation fuel (Fig. 7, left part). At its peak in 1943, half of all fuel consumed in Germany was synthetic fuels. Production was abandoned when cheap oil re-entered the market after the war (Higman and van der Burgt, 2008). The technology had, however, spread to South Africa, where a first plant was built in 1955. Due to a threatening embargo related to international outrage over the apartheid system, production was expanded, and in the 1970s, synthetic fuels covered half of the demand. The technology did not spread to other countries until the mid-1990s, when a dozen plants were built in China (GASIF, 2007). However, when oil prices plummeted after the financial crisis in 2008, all new projects were abandoned. In conclusion, the system demonstrates a high degree of regional concentration and integration in all periods. However, the spatial positioning of activities has shifted, resulting in a discontinuous spatio-temporal shape (Fig. 7).

In contrast, fuel ethanol started out in the first decades of the 20th century as a regionally distributed system where many countries had production and consumption, enabled by the wide-spread knowledge of how to produce alcoholic beverages. The system was integrated at the national or local level with few international links (Fig. 8, left part). However, with the introduction of globally available cheap oil after World War II, large scale ethanol production mostly disappeared. It would take until the 1970s oil crises before the interest in ethanol took off again. This time the system adopted a spatially concentrated configuration, where growth was first concentrated to Brazil, and later to the USA (Fig. 8, right part). Developments in Brazil and the USA were mainly driven by domestic policy support, but also by a growing European market stimulated by subsidies (Solomon et al., 2007). Eventually, this came to encourage some production in Europe, China and the rest of the world. This resulted in a less spatially concentrated system, where a high degree of trade and technical standardization led to integration at the global rather than regional scale, where producers from around the world shared markets and consumers shared suppliers.

In conclusion, these examples illustrate that spatial configurations can vary substantially between alternative value chains and over time within a more broadly defined sociotechnical system.

5. Discussion and concluding remarks

This paper is based on the argument that efforts to investigate and promote specific directions of change require not only an understanding of innovation dynamics, but also a clear view on the specific characteristics of the directions themselves. We have therefore sought to sketch the contours of a morphology of sociotechnical systems, by unpacking and conceptualizing the multidimensional space in which different system shapes and configurations appear. Our conceptual contribution is illustrated by three empirical examples where directionality has resulted in systems with different technical, social and spatial characteristics.

We do not, however, claim to have developed an exhaustive conceptual framework. On the contrary, our focus has been to start with a few fundamental system dimensions and then explore a multidimensional space of possibility for emerging sociotechnical systems. In particular, we have elaborated on, and empirically illustrated, some characteristics of technical, social and spatial configurations. The end result is a conceptual contribution that may inform analytical efforts interested in specific directions of change rather than growth. In addition, it may serve as a point of departure for future research along several avenues.

To begin with, there are configurational properties to be found beyond the admittedly rather crude categories outlined in this paper. The vast literatures on technology assessment, organizational studies, science and technology studies and geography of innovation, to name a few, could be mined to add nuance and additional configurational properties in technical, social and spatial dimensions.

Another potential research avenue is to develop links between the conceptual contribution presented in this paper and the extant literature that deals with the formation of directionality. Such work could aim to explore the dynamics which underlie development trajectories that lead to different configurations and thereby inform policy efforts to shape innovation towards desirable outcomes. From an empirical perspective, this is essentially about furthering the current understanding of how sociotechnical systems grow as a result of historical path dependencies, system-internal dynamics and external influence, towards a more elaborate understanding of how these mechanisms influence how system configurations change over time. From a conceptual perspective, it is rather about enabling such investigations, by developing analytical frameworks that capture not only the pace, but also the directionality of innovation processes. For example, there may be a need to advance the commonly used technological innovation systems framework, since the typology of functional processes is geared towards investigating system growth in a way that hides the potential for vastly different technical, social and spatial development trajectories (Andersson, 2020).

Future research could also strengthen and develop the links in the opposite direction, by focusing on the effects of different shapes and configurations. Although the configurational properties discussed in this paper are strongly related to positive and negative consequences associated with emerging technologies, our contribution stops at outlining configurational properties of sociotechnical systems and says little about the effects of these properties in society and nature. This is the realm of assessment studies. However, by developing interfaces to, on the one hand innovation studies as outlined above, and on the other, assessment studies, the presented conceptual ideas could form a link in a chain of analysis connecting intervention in sociotechnical systems to desirable and undesirable consequences (Andersson and Jacobsson, 2000; Sandén and Karlström, 2007; Schot and Rip, 1996). Even though such an ambition may sound like an overly rationalistic social engineering project, that kind of analyses could just as well be used as a critical tool (Jackson 2001, Stirling 2019), in particular given the appreciation of uncertainty and agency in the innovation literature. Such an endeavor could thus open (Stirling 2008), rather than close, debates on technological pathways, risks and opportunities, and appropriate technology policy, firm strategy and citizen action.

Finally, there is certainly a need to test, validate and strengthen the ideas presented in this paper through empirical case studies. The illustrative examples of different configurations provided in Section 4 suggest how such investigations could be approached, but more extensive empirical data (and additional space to elaborate on retrospective and prospective narratives) is called for in order to properly demonstrate the merits of our contribution.

To conclude, our ambition with this paper is to take steps towards a morphology of sociotechnical systems. We present a conceptual contribution that may broaden and sharpen discussions on directionality in ways that accounts for the multidimensional nature of sociotechnical change. In the end, we hope that this will serve as a starting-point for intensified efforts to reintegrate scholarly and policy attention to the dynamics and consequences of technological innovation.

Declaration of Competing Interest

None.

Acknowledgements

The research presented in this paper was funded by the Swedish Energy Agency (Grant no. 39885-1) and by the Kamprad Family Foundation. The usual disclaimer applies.

References

Abernathy, W., Utterback, J.M., 1978. Patterns of Industrial Innovation. Technol. Rev. 80, 40–47.

Ahlborg, H., Ruiz-mercado, I., Molander, S., Masera, O., 2019. Bringing Technology into Social-Ecological Systems Research — Motivations for a Socio-Technical-Ecological Systems Approach. Sustainability. https://doi.org/10.3390/su11072009.

Andersson, B.A., Jacobsson, S., 2000. Monitoring and assessing technology choice: The case of solar cells. Energy Policy 28, 1037–1049. https://doi.org/10.1016/S0301-4215(00)00090-2.

Andersson, J., 2020. Shaping innovation. Dr. thesis. Chalmers University of Technology, Gothenburg, Sweden.

Andersson, J., Hellsmark, H., Sandén, B., 2021. Photovoltaics in Sweden – Success or failure? Renew. Sustain. Energy Rev. 143 https://doi.org/10.1016/j.rser.2021.110894.

Andersson, J., Hellsmark, H., Sandén, B.A., 2018. Shaping factors in the emergence of technological innovations: The case of tidal kite technology. Technol. Forecast. Soc. Change 132, 191–208. https://doi.org/10.1016/j.techfore.2018.01.034.

Arthur, B.W., Dosi, G., Freeman, C., Nelson, R., Silverberg, G., 1988. Competing technologies: an overview. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishers, London, pp. 590–607.

Arthur, B.W., 2009. The Nature of Technology: What It Is and How It Evolves. Free Press, New York.

Ayres, R.U., 1969. Technological forecasting and long-range planning. McGraw-Hill, New York.

Azar, C., Sandén, B.A., 2011. The elusive quest for technology-neutral policies. Environ. Innov. Soc. Transitions 1, 135–139. https://doi.org/10.1016/j.eist.2011.03.003.

Balland, P.-A., Boschma, R., Frenken, K., 2015. Proximity and Innovation: From Statics to Dynamics. Regional Studies 49 (6), 907–920. https://doi.org/10.1080/00343404.2014.883598.

Banse, G., Grunwald, A., Imre, H., Nelson, G., 2011. On Prospective Technology Studies. KIT SCIENTIFIC REPORTS 7599.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transitions 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008a. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Res. Policy 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bergek, A., Jacobsson, S., Sandén, B.A., 2008b. 'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems. Technol. Anal. Strateg. Manag. 20, 575–592. https://doi.org/10.1080/09537320802292768.

Bertalanffy, L., 1968. General Systems Theory. General Systems Theory. George Braziller, New York.

Binz, C., Tang, T., Huenteler, J., 2017. Spatial lifecycles of cleantech industries – The global development history of solar photovoltaics. Energy Policy 101. https://doi.org/10.1016/j.enpol.2016.10.034.

Binz, C., Truffer, B., 2017. Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts. Res. Policy 46, 1284–1298. https://doi.org/10.1016/j.respol.2017.05.012.

Binz, C., Truffer, B., Coenen, L., 2015. Path Creation as a Process of Resource Alignment and Anchoring: Industry Formation for On-Site Water Recycling in Beijing. Econ. Geogr. 00, 1–29. https://doi.org/10.1080/00130095.2015.1103177.

Branscomb, L.M., 1973. Federal Support of Commercially Relevant R&D: R&D directed toward improving the knowledge environment and the technology delivery system can produce more benefits than direct federal financial incentives to industry. Am. Sci. 61, 144–151.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1, 93–118.

Churchman, C.W., 1970. Operations Research as a Profession. Manage. Sci. 17.
Churchman, C.W., 1967. Wicked Problems. Manage. Sci. 14.
Coates, V.T., 1972. Technology and Public Policy. The Process of Technology Assessment in the Federal Government. Summary report. Washington, D.C.
Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. J. Clean. Prod. 18, 1149–1160. https://doi.org/10.1016/j.jclepro.2010.04.003.
Cooke, P., 2002. Knowledge economies: Clusters, learning and cooperative advantage. Routledge, London and New York.
Cooke, P., Gomez Uranga, M., Etxebarria, G., 1997. Regional innovation systems: Institutional and organisational dimensions. Res. Policy 26, 475–491. https://doi.org/10.1016/S0048-7333(97)00025-5.
Cowan, R., Foray, D., 2002. Evolutionary economics and the counterfactual threat: On the nature and role of counterfactual history as an empirical tool in economics. J. Evol. Econ. 12, 539–562. https://doi.org/10.1007/s00191-002-0134-8.
David, P.A., 1985. Clio and the Economics of QWERTY. Am. Econ. Rev. 75, 332–337.
de Jouvenel, B., 1967. The art of conjecture. Basic Books Inc.
de Jouvenel, H., 2019. Futuribles: Origins, Philosophy, and Practices—Anticipation for Action. World Futur. Rev. 11, 8–18. https://doi.org/10.1177/1946756718777490.
Dewald, U., Fromhold-Eisebith, M., 2015. Trajectories of sustainability transitions in scale-transcending innovation systems: The case of photovoltaics. Environ. Innov. Soc. Transitions 17, 110–125. https://doi.org/10.1016/j.eist.2014.12.004.
Dosi, G., 1982. Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change. Res. Policy 11, 147–162. https://doi.org/10.1016/0048-7333(82)90016-6.
Edler, J., Boon, W.P., 2018. The next generation of innovation policy: Directionality and the role of demand-oriented instruments'—Introduction to the special section. Sci. Public Policy 45, 433–434. https://doi.org/10.1093/scipol/scy026.
EIA, 2019. Biofuels [WWW Document]. U.S. Energy Inf. Adm.
Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Assess. 9, 161–171. https://doi.org/10.1007/BF02994190.
Eldredge, N., Gould, S.J., 1972. Punctuated equilibria - an alternative to phyletic gradualism. In: Schopf, T.J.M. (Ed.), Models in Paleobiology. Freeman Cooper, San Francisco, pp. 82–115.
Elzen, B., Geels, F.W., Leeuwis, C., Van Mierlo, B., 2011. Normative contestation in transitions "in the making": Animal welfare concerns and system innovation in pig husbandry. Res. Policy 40, 263–275. https://doi.org/10.1016/j.respol.2010.09.018.
EU, 2009. DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
European Commission - Joint Research Centre, 2010. European Commission - Joint Research Centre -Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance, First edition. EUR 24708 EN. Publications Office of the European Union, Luxembourg. March 2010.
Fogelberg, H., Sanden, B., 2008. Understanding reflexive systems of innovation: An analysis of Swedish nanotechnology discourse and organization. Technol. Anal. Strateg. Manag. 20, 65–81. https://doi.org/10.1080/09537320701726593.
Foray, D., Grübler, A., 1996. Technology and the Environment: An Overview. Technol. Forecast. Soc. Chang. 53, 1–13. https://doi.org/10.1002/9780470696088.ch7.
Foray, D., Grübler, A., 1990. Morphological analysis, diffusion and lockout of technologies: Ferrous casting in France and the FRG. Res. Policy 19, 535–550. https://doi.org/10.1016/0048-7333(90)90011-T.
Gabor, D., 1963. Inventing the future. Secker & Warburg, London.
GASIF, 2007. Gasification World Survey Results. National Energy Technology Laboratory, U.S Department of Energy.
Geels, F.W., 2005. The Dynamics of Transitions in Socio-technical Systems: A Multi-level Analysis of the Transition Pathway from Horse-drawn Carriages to Automobiles (1860–1930). Technol. Anal. Strateg. Manag. 17, 445–476. https://doi.org/10.1080/09537320500357319.
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Res. Policy 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Georghiou, L., Harper, J.C., Keenan, M., Miles, I., Popper, R., 2008. The Handbook of Technology Foresight. Edward Elgar Publishing, Cheltenham, UK.
Green, K., Randles, S., 2006. Chapter 1: At the Interface of Innovation Studies and Industrial Ecology. In: Green, K., Randles, S. (Eds.). Edward Elgar Publishing, Northhampton, Massachusetts. https://doi.org/10.4337/9781847202956.
Greenea, 2017. New players join the HVO game. February 22. Greenea, Coivert, France.
Grillitsch, M., Hansen, T., Coenen, L., Miörner, J., Moodysson, J., 2018. Innovation policy for system-wide transformation: The case of strategic innovation programmes (SIPs) in Sweden. Res. Policy 1–14. 10.1016/j.respol.2018.10.004.
Heidegger, M., 1977. The Question Concerning Technology, and Other Essays. Garland Publishing.
Hekkert, M.P., Janssen, M.J., Wesseling, J.H., Negro, S.O., 2020. Mission-oriented innovation systems. Environ. Innov. Soc. Transitions 34, 76–79.
Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.
Hellsmark, H., Hansen, T., 2020. A new dawn for (oil) incumbents within the bioeconomy? Trade-offs and lessons for policy. Energy Policy 145, 111763. https://doi.org/10.1016/j.enpol.2020.111763.
Hidalgo, C.A., Hausmann, R., 2009. The building blocks of economic complexity. Proceedings of the National Academy of Sciences 106 (26), 10570–10575. https://doi.org/10.1073/pnas.0900943106.
Higman, C., van der Burgt, M., 2008. Gasification. Gulf Professional Publishing, Burlington, USA.
Hillman, K.M., Sandén, B.A., 2008. Exploring technology paths: The development of alternative transport fuels in Sweden 2007–2020. Technol. Forecast. Soc. Change 75, 1279–1302. https://doi.org/10.1016/j.techfore.2008.01.003.
Hojcková, K., Sandén, B., Ahlborg, H., 2018. Three electricity futures: Monitoring the emergence of alternative system architectures. Futures 98, 72–89. https://doi.org/10.1016/j.futures.2017.12.004.
Holmberg, J., Robert, K.-H., 2000. Backcasting — a framework for strategic planning. Int. J. Sustain. Dev. World Ecol. 7, 291–308. https://doi.org/10.1080/13504500009470049.
Hughes, Thomas P., 1987. The Evolution of Large Technological Systems, in: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge.
Håkansson, H., 1990. Technological collaboration in industrial networks. European Management Journal 8 (3), 371–379. https://doi.org/10.1016/0263-2373(90)90016-Y.
E.S. IPBES, 2019. In: Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M. (Eds.), Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E.S.J.
IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.
IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
IRENA, 2014. The Socio-economic Benefits of Solar and Wind Energy. International Renewable Energy Agency.
Jackson, M.C., 2001. Critical systems thinking and practice. Eur. J. Oper. Res. 128, 233–244. https://doi.org/10.1016/S0377-2217(00)00067-9.

Jacobsson, S., Sandén, B., Bångens, L., 2004. Transforming the Energy System — the Evolution of the German Technological System for Solar Cells. Technol. Anal. Strateg. Manag. 16, 3–30. https://doi.org/10.1080/0953732032000199061.

Jantsch, E., 1967. Technological Forecasting in Perspective: A Framework for Technological Forecasting. its Techniques and Organisation.

Joas, F., Pahle, M., Flachsland, C., Joas, A., 2016. Which goals are driving the Energiewende? Making sense of the German Energy Transformation. Energy Policy 95, 42–51. https://doi.org/10.1016/j.enpol.2016.04.003.

Kanger, L., Schot, J., 2018. Deep transitions: Theorizing the long-term patterns of socio-technical change. Environ. Innov. Soc. Transitions 0–1. https://doi.org/10.1016/j.eist.2018.07.006.

Kauppila, I., 2018. BIOFUELS HVO making it big. Biofuels November/D.

Kemp, R., 1994. Technology and the transition to environmental sustainability. The problem of technological regime shifts. Futures 26, 1023–1046. https://doi.org/10.1016/0016-3287(94)90071-X.

Kemp, R., Loorbach, D., 2006. 5. Transition management: a reflexive governance approach, in: Voß, J.-P., Bauknecht, D., Kemp, R. (Eds.), Reflexive Governance for Sustainable Development. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA.

Kemp, R., Soete, L., 1992. The greening of technological progress. An evolutionary perspective. Futures 24, 437–457. https://doi.org/10.1016/0016-3287(92)90015-8.

Köhler, J., Geels, F.W., Kern, F., Köhler, J., Geels, F.W., Kern, F., Markard, J., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., Mcmeekin, A., Susan, M., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., A, B.T., B, D.W., Mühlemeier, M.S., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., Köhler, J., Geels, F.W., Kern, F., Markard, J., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., Mcmeekin, A., Susan, M., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., A, B.T., B, D.W., 2019. An agenda for sustainability transitions research: State of the art and future directions. Environ. Innov. Soc. Transitions 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Kuhlmann, S., Rip, A., 2018. Next-generation innovation policy and Grand Challenges. Sci. Public Policy 45, 448–454. https://doi.org/10.1093/SCIPOL/SCY011.

Kuhn, T.S., 1970. The Structure of Scientific Revolutions, Philosophical Review. https://doi.org/10.1119/1.1969660.

Liedman, S.-E., 1997. I skuggan av framtiden: modernitetens idéhistoria. Albert Bonniers Förlag, Stockholm.

Lindner, R., Daimer, S., Beckert, B., Heyen, N., Köhler, J., Teufel, B., Warnke, P., Wydra, S., 2016. Addressing directionality: Orientation failure and the systems of innovation heuristic. Towards reflexive governance. Fraunhofer ISI Discussion Papers Innovation Systems and Policy Analysis.

Loorbach, D., 2010. Transition management for sustainable development: A prescriptive, complexity-based governance framework. Governance 23, 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x.

Loorbach, D., Rotmans, J., 2010. The practice of transition management: Examples and lessons from four distinct cases. Futures 42, 237–246. https://doi.org/10.1016/j.futures.2009.11.009.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Res. Policy 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Markard, J., Stadelmann, M., Truffer, B., 2009. Prospective analysis of technological innovation systems: Identifying technological and organizational development options for biogas in Switzerland. Res. Policy 38, 655–667. https://doi.org/10.1016/j.respol.2009.01.013.

Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Res. Policy 37, 596–615. https://doi.org/10.1016/j.respol.2008.01.004.

Marshall, A., 1890. Principles of Economics. Macmillan & Co, London, UK.

Mazzucato, M., 2018. Mission-oriented innovation policies: challenges and opportunities. Ind. Corp. Chang. 27, 803–815. https://doi.org/10.1093/icc/dty034.

Mazzucato, M., 2016. From market fixing to market-creating: a new framework for innovation policy. Ind. Innov. 23, 140–156. https://doi.org/10.1080/13662716.2016.1146124.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The Limits to Growth: A report to the club of rome. Universe Books, New York. https://doi.org/10.1111/j.1752-1688.1972.tb05230.x.

Merriam-Webster, 2020. "System" [WWW Document]. Merriam-Webster Dict. URL https://www.merriam-webster.com/dictionary/system (accessed 8.20.20).

Nelson, R.R., Winter, S.G., 1982. An evolutionary theory of economic change. Belknap Press of Harward University Press, London.

Nelson, R.R., Winter, S.G., 1977. In search of usefult theory of innovation. Res. Policy 6, 36–76.

Owen, R., Bessant, J., Heintz, M., 2013. Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society. John Wiley & Sons Ltd.

Page, T., 1967. The Nature of Operations Research and its Beginnings. In: Zwicky, F., Wilson, A.G. (Eds.), New Methods of Thought and Procedure. Springer-Verlag New York Inc., New York.

Pel, B., Boons, F.A., 2010. Transition through subsystem innovation? The case of traffic management. Technol. Forecast. Soc. Change 77, 1249–1259. https://doi.org/10.1016/j.techfore.2010.04.001.

Pel, B., Raven, R., van Est, R., 2020. Transitions governance with a sense of direction: synchronization challenges in the case of the dutch 'Driverless Car' transition. Technol. Forecast. Soc. Change 160, 120244. https://doi.org/10.1016/j.techfore.2020.120244.

Pigford, A.A.E., Hickey, G.M., Klerkx, L., 2018. Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. Agric. Syst. 164, 116–121. https://doi.org/10.1016/j.agsy.2018.04.007.

Pinch, T.J., Bijker, W.E., 1987. The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other, in: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge.

Pintar, N., Scherngell, T., 2021. The complex nature of regional knowledge production: Evidence on European regions. Research Policy, 104170. https://doi.org/10.1016/j.respol.2020.104170.

Porter, A.L., Roper, A.T., Mason, T.W., Rossini, F.A., Banks, J., 1991. Forecasting and management of technology. John Wiley & Sons, New York.

Porter, M.E., 1990. The Competitive Advantage of Nations. Harv. Bus. Rev. 73–93.

Powell, W.W., 1990. Neither market nor hierarchy: Network forms of organization. Res. Organ. Behav. 12, 295–336.

Quitzow, R., 2015. Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. Environ. Innov. Soc. Transitions 17, 126–148. https://doi.org/10.1016/j.eist.2014.12.002.

Rip, A., Kemp, R., 1998. Technological change, in: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Battelle Press, Columbus, OH, pp. 327–399. 10.1007/BF02887432.

Ritchey, T., Arciszewski, T., 2018. Editors' introduction. Technol. Forecast. Soc. Change 126, 76–80. https://doi.org/10.1016/j.techfore.2017.02.036.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a General Theory of Planning *. Policy Sci 4, 155–169.

Robinson, J.B., 1982. Energy backcasting: A proposed method of policy analysis. Energy Policy 10, 337–344. https://doi.org/10.1016/0301-4215(82)90048-9.

Røpke, I., 2012. The unsustainable directionality of innovation - The example of the broadband transition. Res. Policy 41, 1631–1642. https://doi.org/10.1016/j.respol.2012.04.002.

Rotmans, J., Kemp, R., van Asselt, M., 2001. More evolution than revolution: transition management in public policy. Foresight 3, 15–31. https://doi.org/10.1108/14636690710816471.

Sahal, D., 1981. Alternative conceptions of technology. Res. Policy 10, 2–24.

Sandén, B.A., 2004. Technology path assessment for sustainable technology development. Innov. Manag. policy Pract. 6, 316–330.

Sandén, B.A., Hillman, K.M., 2011. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Res. Policy 40, 403–414. https://doi.org/10.1016/j.respol.2010.12.005.

Sandén, B.A., Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. J. Clean. Prod. 15, 1469–1481. https://doi.org/10.1016/j.jclepro.2006.03.005.

Sartorius, C., Zundel, S., 2005. Time Strategies, Innovation and Environmental Policy. Edward Elgar Publishing.

Saviotti, P.P., 1986. Systems theory and technological change. Futures 18, 773–786. https://doi.org/10.1016/0016-3287(86)90126-6.
Saxenian, A., 1996. Regional Advantage: Culture and Competition in Silicon Valley and Route 128. Harvard University Press, Cambridge, Massachusetts. https://doi.org/10.2307/j.ctvjnrsqh.
Saxenian, A.L., 1990. Regional Networks and the Resurgence of Silicon Valley. Calif. Manage. Rev. 33, 89–112. https://doi.org/10.2307/41166640.
Schlaile, M.P., Urmetzer, S., Blok, V., Andersen, A.D., Timmermans, J., Mueller, M., Fagerberg, J., Pyka, A., 2017. Innovation systems for transformations towards sustainability? Taking the normative dimension seriously. Sustain. 9. 10.3390/su9122253.
Schot, J., Kanger, L., 2018. Deep transitions: Emergence, acceleration, stabilization and directionality. Res. Policy 47, 1045–1059. https://doi.org/10.1016/j.respol.2018.03.009.
Schot, J., Rip, A., 1996. The Past and Future of Constructive Technology Assessment. Technol. Forecast. Soc. Change 54, 251–268. https://doi.org/10.1016/s0040-1625(96)00180-1.
Scordato, L., Bugge, M.M., Fevolden, A.M., 2017. Directionality across diversity: Governing contending policy rationales in the transition towards the bioeconomy. Sustain. 9, 1–14. 10.3390/su9020206.
Simon, H.A., 1962. The Architecture of Complexity. Proc. to Am. Philos. Soc. 106.
Solomon, B.D., Barnes, J.R., Halvorsen, K.E., 2007. Grain and cellulosic ethanol: History, economics, and energy policy. Biomass and Bioenergy 31, 416–425. https://doi.org/10.1016/j.biombioe.2007.01.023.
Sovacool, B.K., 2021. When subterranean slavery supports sustainability transitions? power, patriarchy, and child labor in artisanal Congolese cobalt mining. Extr. Ind. Soc. 8, 271–293. https://doi.org/10.1016/j.exis.2020.11.018.
Stirling, A., 2019. How deep is incumbency? A 'configuring fields' approach to redistributing and reorienting power in socio-material change. Energy Res. Soc. Sci. 58 https://doi.org/10.1016/j.erss.2019.101239.
Stirling, A., 2011. Pluralising progress: From integrative transitions to transformative diversity. Environ. Innov. Soc. Transitions 1, 82–88. https://doi.org/10.1016/j.eist.2011.03.005.
Stirling, A., 2010. Multicriteria diversity analysis: A novel heuristic framework for appraising energy portfolios. Energy Policy 38 (4), 1622–1634. https://doi.org/10.1016/j.enpol.2009.02.023.
Stirling, A., 2009. Direction, Distribution and Diversity! Pluralising Progress in Innovation. Sustainability and Development. STEPS Work. Pap. 32, 1–45.
Stankiewicz, R., 2000. The concept of 'design space'. In: Ziman, J. (Ed.), Technological Innovation as an Evolutionary Process. Cambridge University Press, New York, pp. 234–247.
Stirling, A., 2008. Opening up" and "closing down": Power, participation, and pluralism in the social appraisal of technology. Sci. Technol. Hum. Values 33, 262–294. https://doi.org/10.1177/0162243907311265.
Suurs, R.A.A., Hekkert, M.P., 2009. Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands. Energy 34, 669–679. https://doi.org/10.1016/j.energy.2008.09.002.
Sveiby, K.-E., Gripenberg, P., Segercrantz, B., 2012. Challenging the Innovation Paradigm. Routledge, New York and London.
Swanson, A., Buckley, C., 2021. Chinese Solar Companies Tied to Use of Forced Labor. New York Times.
te Kulve, H., Boon, W., Konrad, K., Schuitmaker, T.J., 2018. Influencing the direction of innovation processes: The shadow of authorities in demand articulation. Sci. Public Policy 45, 455–467. https://doi.org/10.1093/SCIPOL/SCY015.
Ulrich, W., 2003. Beyond methodology choice: Critical systems thinking as critically systemic discourse. J. Oper. Res. Soc. 54, 325–342. https://doi.org/10.1057/palgrave.jors.2601518.
UN, 2020. World Social Report 2020: Inequality in a rapidly changing world, World Social Report 2020. Department of Economic and Social Affairs, United Nations. https://doi.org/10.18356/7f5d0efc-en.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830. https://doi.org/10.1016/S0301-4215(01)00098-2.
Uyarra, E., Ribeiro, B., Dale-Clough, L., 2019. Exploring the normative turn in regional innovation policy: responsibility and the quest for public value. Eur. Plan. Stud. 27, 2359–2375. https://doi.org/10.1080/09654313.2019.1609425.
Van Den Bergh, J.C.J.M., Truffer, B., Kallis, G., 2011. Environmental innovation and societal transitions: Introduction and overview. Environ. Innov. Soc. Transitions 1, 1–23. https://doi.org/10.1016/j.eist.2011.04.010.
WCED, 1987. Report by the World Commision on Environment and Development. Our Common future. Oxford University Press.
Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change. Res. Policy 41, 1037–1047. https://doi.org/10.1016/j.respol.2011.10.015.
Wieczorek, A.J., Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Sci. Public Policy 39, 74–87. https://doi.org/10.1093/scipol/scr008.
Wiener, N., 1948. Cybernetics – Control and Communication in the Animal and the Machine. John Wiley, New York.
Yap, X.S., Truffer, B., 2018. Shaping selection environments for industrial catch-up and sustainability transitions: A systemic perspective on endogenizing windows of opportunity. Res. Policy 48, 1030–1047. https://doi.org/10.1016/j.respol.2018.10.002.
Zhang, F., Gallagher, K.S., 2016. Innovation and technology transfer through global value chains: Evidence from China's PV industry. Energy Policy 94, 191–203. https://doi.org/10.1016/j.enpol.2016.04.014.
Zwicky, F., 1967. The Morphological Approach to Discovery, Invention, Research and Construction. In: Zwicky, F., Wilson, A.G. (Eds.), New Methods of Thought and Procedure. Springer-Verlag New York Inc., New York.